Guidance Document on Management of Methane Gas Adjacent to Landfills

Prepared for:

ALBERTA ENVIRONMENTAL PROTECTION
203, 2938 – 11 Street N.E.
Calgary, Alberta T2E 7L7

Prepared by:

CG&S
CH2M Gore & Storrie Limited

November 1999

Table of Contents

Appendices

Figures

Tables

List of Abbreviations

kPa	Kilo Pascals
LEL	Lower explosive limit
LFG	Landfill gas
m	Metre
MSW	Municipal Solid Waste
NMOC	Non-methane organic compounds
PE	Polyethylene
ppb	Parts per billion
ppm	Parts per million
psi	Pounds per square inch
PVC	Polyvinyl chloride
QA/QC	Quality Assurance/Quality Control
STEL	Short-term exposure limit
TLV	Threshold limit value
UEL	Upper explosive limit
USEPA	United States Environmental Protection Agency
VC	Vinyl Chloride
VOC	Volatile Organic Compound

Glossary of Terms

Air emissions	For stationary sources, the release or discharge of a pollutant from a facility or operation into the ambient air either by means of a stack or as a fugitive dust, mist or vapour.
Ambient air	That portion of the atmosphere external to buildings to which the general public has access.
Anaerobic	The biological state of living and growing in the absence of oxygen.
Barhole probe	A steel rod that is hammered into the soil to an approximate depth of one metre to allow sampling or measurement of soil vapours in the resulting void.
Carbon dioxide	One of the principle gases which comprises landfill gas. A greenhouse gas. Also the major product of hydrocarbon combustion.
Clay	Inorganic soil particles of size smaller than 0.005 mm.
Combustible	Able to undergo a chemical reaction resulting in release of both heat and light; typically in combination with oxygen.
Commercial solid waste	Non-hazardous solid waste that is generated from commercial establishments.
Concentration	The relative fraction of one substance in another, normally expressed in mass percent, mass/volume, volume percent (% v/v) or as a percentage of the lower explosive limit (%LEL).
Contaminant	Means any solid, liquid, gas, odour, heat, sound, vibration, radiation or combination thereof, resulting directly or indirectly from human activities and that may cause an adverse effect.
Diffusion	Migration of molecules or ions in air or water as a result of their own random movements from a region of higher concentration to a region of lower concentration. Diffusion can occur in the absence of any bulk air or water movement.
Dilution	Increasing the proportion of solvent to solute in solution, and thereby decreasing the concentration of solute per unit volume.
Dispersion modelling	The calculation of ambient air concentrations of a subject pollutant by means of computer algorithms.
Domestic waste	Non-hazardous solid waste generated form households. Also referred to as residential waste or municipal solid waste (MSW). It does not include liquid or hazardous waste.
Emission rate	The amount of pollutant emitted per unit of time.

Emissions	In air, pollutants in the form of gases or fine particles released into the atmosphere, usually from a stack.
Explosion	Extremely rapid combustion of a compound resulting in an increase in volume and creation of pressures when enclosed.
Explosive limit	The range of concentrations in air within which a compound is explosive. Methane forms explosive mixture when mixed with air in the range of 5 to 15 percent by volume. 5% by volume is referred to as the lower explosive limit (LEL) of methane in air. 15% by volume is referred to as the upper explosive limit (UEL) of methane in air.
Flammable	Able to ignite.
Flux	The amount (mass or volume) of a substance flowing across a given area per unit time.
Hydraulic conductivity	The ability of soil or rock to transmit liquid. The higher the hydraulic conductivity, the greater the ability to transmit fluid.
Landfill	A land-based disposal site for municipal solid waste, employing an engineered method of disposing of wastes on land under controlled conditions (see landfilling).
Landfill gas (LFG)	The mixture of gases generated by the decomposition of putrescible organic wastes.
Landfilling	Disposal of waste by deposit, under controlled conditions on land in a manner that minimizes environmental hazards by spreading wastes in thin layers, compacting the wastes to the smallest practical volume, and applying cover materials at the end of each operating day.
LFG collection rate	The quantity of LFG that is extracted from a site in a given period.
LFG control	Collection and disposal (i.e. flaring) of LFG for the purpose of controlling potential environmental impacts.
LFG emission	The portion of LFG production that is released to the atmosphere (i.e. does not include LFG that is collected or migrates into the surrounding soil).
LFG generation rate	The quantity of LFG that results from decomposition of a unit of refuse in a given period.
LFG management	LFG control with LFG utilization as an alternative to flaring.
LFG production rate	The total quantity of LFG generated by the total amount of refuse in a site at a given time.
LFG recovery rate	Similar to LFG collection, however generally applied only in the context of LFG utilization.

LFG utilization	Use of collected LFG as a fuel or for use as an input in a production process.
LFG yield	The total quantity of LFG that is given off by a unit mass of refuse. The quantity is highly dependent upon the character of the waste.
Liner	Compacted natural clayey soil or manufactured material, i.e. plastic, which serves as a barrier to control the amount of leachate that reaches or mixes with groundwater.
Mercaptans (Thiol)	Group of organic compounds having the oxygen of the hydroxyl group (OH) replaced by sulfur. Many thiols are characterized by strong and repulsive odours at very low concentrations (ppb-range).
Methane (CH_4)	An odourless, colourless, non-poisonous gas which is explosive when mixed with air or oxygen in certain proportions. It is a greenhouse gas.
Migration	LFG movement from one place to another, moving under natural forces.
Municipal solid waste (MSW)	Consists of domestic or residential waste and industrial, commercial and institutional waste of similar composition in any combination, but does not include liquid or hazardous waste.
Permeable	Permitting the flow of water or other liquids; the property of a solid material that allow fluids to flow through it.
Point of emission	The point at which a contaminant enters the natural environment.
Point of entry	The point at which the gas enters into the building.
PPB/ppb:	Parts per billion (mass of substance (mg)/mass of solution (1,000kg).
PPM/ppm	Parts per million (mass of substance (mg)/mass of solution (kg).

1. Introduction

1.1 Background

Significant economic development in the Province of Alberta has led to increased pressure for development of land adjacent to landfills. Methane gas migration from these landfills may pose a potential hazard to the occupants of these properties. At present, no guidelines exist in the Province of Alberta for the assessment and management of methane gas. In order to accommodate existing and proposed developments adjacent to active and inactive landfills, Alberta Environmental Protection (AEP) funded the development of this guidance document on the management of methane gas and its potential impacts. The terms of reference for and review of this document were developed jointly by representatives of AEP, City of Calgary Solid Waste Services and Calgary Regional Health Authority.

1.2 Purpose of This Document

This document was prepared to provide the Provincial and Municipal levels of government, as well as land developers, with guidance concerning the management of methane gas around landfills. This document is an information document and was not intended for regulatory purposes. The document is based on a review of policies, guidelines, and regulations in other jurisdictions throughout North America, and includes reviews of various technical aspects of methane migration and its impacts.

2. Action Level Criteria

2.1 Regulatory and Literature Overview

A review of Canadian and U.S. legislation and related literature was conducted to identify existing and proposed regulatory requirements and procedures for management of methane gas on and adjacent to active and inactive landfills. Appendix A contains a list of all documents included in the regulatory and literature review.

The regulatory review indicated that only a few jurisdictions in Canada and the U.S. have developed regulations regarding management of methane gas originating from landfills. As shown in Table 2-1, only three Canadian jurisdictions have such regulations in place. These jurisdictions are Ontario, Quebec and British Columbia. In the U.S., pertinent regulations were developed at a federal level by the US Environmental Protection Agency (US EPA), and by state agencies in New Jersey, Pennsylvania, Illinois, Alabama and California. The regulations in all these jurisdictions were developed primarily to set criteria and standards for landfill design and operation.

Generally, regulators consider methane gas migration an issue related to landfill operations. Therefore, the action level criteria related to concentrations of methane gas in on- or off-site structures were developed from the operational perspective. Typically, landfill owners are required to operate their landfills in a manner that will ensure that the concentration of methane gas in on- or off-site buildings does not exceed a pre-determined limit. The owners are expected to periodically monitor concentrations of methane gas within the perimeter of the landfill. If the regulatory limits are exceeded, the landfill owner is responsible for implementing methane gas migration control and mitigation measures. Some of the jurisdictions (e.g., US EPA, British Columbia) have recently added regulations to address air emissions from landfills, in addition to regulating methane concentrations in on- or off-site soils and structures. The additional requirements are for assessment of emissions of non-methane organic compounds (NMOCs), such as volatile organic hydrocarbons, vinyl chloride and mercaptans. NMOCs are used because many are toxic and/or reactive gases that pose more significant concern with respect to human health than methane when emitted to the ambient air.

The literature review indicated that, over the past 10 years, a number of municipalities across Canada and in the U.S. have encountered problems with methane gas on properties adjacent to landfill sites. However, none of the reviewed regulations contained any information on required or recommended methane gas management strategies and monitoring programs specific to properties and structures adjacent to landfills.

TABLE 2-1
LEGISLATION RELATING TO MANAGEMENT OF METHANE GAS FROM LANDFILLS

Jurisdiction	Regulation/Guideline
Canada	
Ontario	Guidance Manual for Landfill Sites Receiving Municipal Waste (November, 1993)
	Guideline D-4, "Land Use On or Near Landfills and Dumps" (April 1994)
	New Standards for Landfill Sites, Proposed Regulatory Standards for New Landfilling Sites Accepting Non-Hazardous Waste (June, 1996)
British Columbia	Landfill Criteria for Municipal Solid Waste (June, 1993)
Quebec	Projet de reglement sur les dechets solides, version technique (March 1994)
United States	
US EPA	Resource Conservation and Recovery Act (RCRA), Subtitle D (October, 1991)
	Clean Air Act, Proposed New Source Performance Standards and Emission Guidelines (NSPS), 40 CFR, Part 60
New Jersey	Solid and Hazardous Waste Management Regulations, Title 7
California (SCQAMD(1))	Control of Gaseous Emissions from Active and Inactive Landfills (Regulation XI)
Pennsylvania	Municipal Waste Management Regulations, Title 25, Chap. 288, C
Illinois	Solid Special Waste Management Regulations, Title 35, Subtitle G
Alabama	Solid Waste Management Regulations, Dept. 355, Div. 13, Chap. 4

(1) South Coast Air Quality Management District

A telephone survey determined that almost all municipalities dealt with methane gas problems on a case-specific basis. In most cases, monitoring programs and migration control measures developed by qualified professionals were put in place, but no policies or guidelines that would apply to all existing or future cases were developed. The only municipality identified in our survey that has developed a guideline for management of methane gas in buildings adjacent to landfills is the City of Winnipeg (Ref. 1). A list of municipalities that were contacted is presented below, and names of all the contacts are listed in Appendix B.

- Edmonton, Alberta
- Calgary, Alberta
- Greater Vancouver Regional District, B.C.
- Coquitlam, B.C.
- Delta, B.C.
- Richmond, B.C.
- Surrey, B.C.
- Winnipeg, Manitoba
- Regional Municipality of Kitchener/Waterloo, Ontario
- London, Ontario
- Oshawa, Ontario
- Metro Toronto, Ontario

- Los Angeles County, California, U.S.
- Seattle King County, Washington, U.S.

The review of the collected legislation and background literature, as well as correspondence with regulatory agencies and various municipalities indicated that the action level criteria were generally selected to provide a comfortable margin of safety compared to the methane lower explosion limit (LEL) of 50,000 ppm. In most cases, safety factors of 4 or 5 (i.e., 25 and 20% of LEL, respectively) were applied resulting in corresponding action levels of 12,500 and 10,000 ppm.

2.2 Properties of Methane Gas

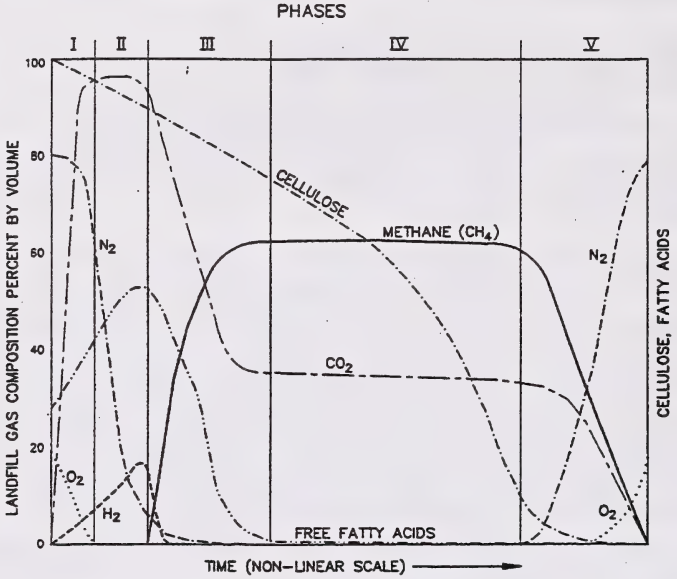
Methane (CH_4) is a colourless, odourless, tasteless, flammable gas that burns with a pale, faintly luminous flame. It is widely distributed in nature and the atmosphere naturally contains 0.00022 percent by volume (2.2 ppm). It is lighter than air and under constant atmospheric conditions it will have a tendency to rise through the air (Ref. 2).

Methane gas is produced wherever organic material is decomposed by bacterial action in the absence of oxygen. As such, it is present in natural gas, swamp gas, sewer gas and is one of the main components of landfill gas (LFG). Landfill gas is typically composed of approximately 50% methane and 50% carbon dioxide, with trace amounts of other organic vapours and gases. However, the proportion of these compounds, as well as the overall quantity and rate of gas production vary with time and from landfill to landfill, because they are a function of numerous factors, including moisture levels in the fill, density, composition, and age of the waste. Note that the density of the mixture of carbon dioxide and methane that is typically found in landfill gas is about the same as air, therefore landfill gas typically does not have a tendency to rise in air, as does pure methane.

The methane content of the LFG is often somewhat higher than that of carbon dioxide, particularly if the gas has migrated some distance from the landfill, because some carbon dioxide dissolves in moisture present in the soil (methane is only marginally soluble in water). Because landfill gas is always of very recent origin, the ratio of carbon 12 to carbon 14 in landfill gas is similar to that in carbon dioxide in the atmosphere (Ref. 7). Landfill gas typically contains traces of volatile organic compounds (VOCs) deposited in the landfill or that result from the breakdown of organic materials in municipal solid waste. Concentrations of these compounds vary widely from landfill site to landfill site, as they depend on the composition of the materials deposited in the landfill (Ref. 8). VOCs which may be found in landfill gas include the BTEX compounds (usually highest in concentration), chlorinated solvents such as perchlorethylene (from dry cleaning wastes), dichloromethane, and other common organic solvents and their breakdown products. Landfill gas may also contain high concentrations (i.e., hundreds of ppm) of hydrogen sulfide and other sulphur compounds, resulting from the breakdown of sulphur-containing materials (including gypsum board) under anaerobic conditions (Ref. 9).

Figure 2-1, illustrates a typical pattern of LFG production over time. It could be expected that, in Alberta, due to lower ambient temperatures and low moisture, LFG production patterns would be follow the upper limits of the typical time frames identified in Figure 2-1.

LANDFILL GAS PRODUCTION PATTERN



PHASES	CONDITION	TIME FRAME – TYPICAL
I	AEROBIC	HOURS TO WEEKS
II	ANOXIC	1 TO 6 MONTHS
III	ANAEROBIC, METHANOGENIC, UNSTEADY	3 MONTHS TO 3 YEARS
IV	ANAEROBIC, METHANOGENIC, STEADY	8 TO 40 YEARS
V	ANAEROBIC, METHANOGENIC, DECLINING	1 TO 40+ YEARS
TOTAL		10 TO 80+ YEARS

SOURCE:
FARQUHAR AND ROVERS, 1973,
AS MODIFIED BY REES, 1980,
AND AUGENSTEIN & PACEY, 1991.

Figure 2-1
Typical Landfill Gas Production Patterns

Source:

Environment Canada, *Guidance Document for Landfill Gas Management*

CGY/98/203C/25804/999F4.CDR

CG&S
CH2M Gore & Storrie Limited

The main concerns associated with methane generation and migration are its flammability and explosiveness. When mixed with air in concentrations between about 50,000 to 150,000 ppm (5 and 15 percent by volume), methane gas forms explosive mixtures, and is therefore a severe fire and explosion hazard. The presence of carbon dioxide (CO_2) affects this range although there is very little effect on the lower explosive limit (LEL). The LEL for methane gas is typically identified as being 50,000 ppm (5 % by volume) in air.

Methane gas is non-toxic, but it is classified as a simple asphyxiant, which means that it causes suffocation by displacing air.

2.3 Indoor Air Methane Concentration

2.3.1 Summary of Background Information

A summary of action level criteria for indoor air obtained from the existing regulations and guidelines in various jurisdictions is presented in Table 2-2.

As shown, most jurisdictions use an indoor-air methane gas concentration of either 10,000 ppm or 12,500 ppm (20% or 25% LEL) as a limit that warrants an action to be taken. In most cases, landfill owners must have a gas monitoring program in place to be able to monitor if these requirements are met. Most jurisdictions do not provide any specifics on frequency or locations where the samples should be collected, as these are required to be determined by a qualified professional on a site-specific basis. If the selected criteria are exceeded, most jurisdictions require that methane gas migration control measures be implemented. Again, appropriate control measures should be recommended by a qualified professional on a site-specific basis. Both the monitoring programs and migration control measures need to be approved by the relevant regulatory body before they can be implemented.

One of the most comprehensive literature sources describing numerous case studies involving methane intrusion into buildings adjacent to landfills is a 1992 report entitled "Study of Houses Affected by Hazardous Lands (Ref. 3), prepared by the Canada Mortgage and Housing Corporation (CMHC). In addition to describing individual case studies and mitigative measures implemented at each site, the report also provides a discussion on action level criteria used at various sites. The report indicates that action level criteria were developed only in a small number of cases, and where they were developed, it was done on an ad-hoc basis (see Table 2-3). The report indicated that the most commonly used criterion in the cases described in the report was a 5,000 ppm (1% LEL) evacuation limit. This criterion is also used in the mining industry. As well, 5,000 ppm is the recommended alarm limit for indoor methane set by the National Fire Code established by the National Fire Protection Association in the U.S.

TABLE 2-2
ACTION LEVEL CRITERIA FOR METHANE CONCENTRATIONS

Jurisdiction	Methane Concentration Limit	Required Action if Limit Exceeded	Regulation/Guideline
Canada			
Ontario	10,000 ppm (20% LEL) in any on-site building or in the area immediately outside the foundation of the building	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume, methane gas migration control measures must be put in place	New Standards for Landfill Sites, Proposed Regulatory Standards for New Landfilling Sites Accepting Non-Hazardous Waste (June, 1996)
	Zero in any off-site building or in the area immediately outside the foundation of the building	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume, methane gas migration control measures must be put in place	
British Columbia	12,500 ppm(25% LEL) in any on- or off-site building	Monitoring program must be prepared and approved by BC Environment authorities	Landfill Criteria for Municipal Solid Waste (June, 1993)
Quebec	12,500 ppm (25% LEL) in air in buildings on or near a landfill	Monitoring program required to record and monitor methane concentrations; if methane concentration exceeds 1% by volume (20% LEL), methane gas migration control measures must be put in place	Projet de reglement sur les dechets solides, version technique (March 1994)
City of Winnipeg	2,500 ppm (5% LEL) mid-air level in a portion of a building	Alarm situation – advise occupants of the building to vacate the premises; provide extra ventilation; shut off sources of ignition; call 911; if the conditions cannot be alleviated, the building will remain vacated. If the situation is stabilized, the City will test the premises daily until long-term protection is provided.	Standards and Guidelines for the Mitigation of Methane Gas at Buildings and Utilities (May 1997)
	10,000 ppm (20% LEL) at any point source in the building	If this concentration is exceeded consistently (i.e., on a monthly basis during a one-year period), measures to mitigate methane gas infiltration must be implemented	
United States			
US EPA	12,500 ppm (25% LEL) in any on-site structure	Must ensure monitoring program is implemented and performed quarterly	Resource Conservation and Recovery Act (RCRA), Subtitle D (October, 1991)
New Jersey	12,500 (25% LEL) inside buildings	Induced draft or active venting system must be installed	Solid and Hazardous Waste Management Regulations, Title 7

TABLE 2-2
ACTION LEVEL CRITERIA FOR METHANE CONCENTRATIONS

Jurisdiction	Methane Concentration Limit	Required Action if Limit Exceeded	Regulation/Guideline
California	No criteria for methane; regulate non-methane organic compounds (NMOCs)		Control of Gaseous Emissions from Active and Inactive Landfills (Regulation XI)

TABLE 2-3
ACTION LEVEL CRITERIA DEVELOPED FOR SPECIFIC CASES

Location	Methane Concentration	Action
Cape Breton, Nova Scotia	5,000 ppm	Evacuation
Kitchener, Ontario	5,000 ppm	Evacuation
Seattle, Washington	5,000 ppm	Evacuation
West Covina, California	Methane > 5% GAS	Evacuation

The CMHC report also provides a fairly detailed description of a case where several levels of action-level criteria were developed for indoor-air methane concentrations in the range below the LEL concentration of 50,000 ppm. The criteria, presented in Table 2-4, were developed in 1986 as part of a response to methane migration problems around the Midway Landfill in Seattle, Washington. The criteria were developed by a committee that included representatives of the Seattle King County Department of Public Health, Washington Department of Ecology, Kent Fire Department, and Solid Waste Division of the City of Seattle Engineering Department. Methane gas was detected as far as three miles away from the landfill. As the number of residential and commercial building potentially affected by methane migration was very large, action level criteria needed to be very conservative to ensure that potentially dangerous conditions were detected early enough to avoid injury to people or damage to property. For the same reasons, the program needed to be comprehensive and gas measurements as frequent as possible. The criteria were developed by a consensus of the committee members.

TABLE 2-4

ACTION LEVEL CRITERIA FOR INDOOR METHANE CONCENTRATIONS (ESTABLISHED AD HOC FOR MIDWAY LANDFILL VICINITY, NEAR SEATTLE, WASHINGTON)

Methane Concentration	Action
0 – 50 ppm	Normal conditions
50 – 100 ppm	Monitor as frequently as staff size permits
100 – 500 ppm	Monitor daily
500 ppm and up	Monitor daily, seal cracks, request owner to ventilate
1,000 ppm and up	Verify with second instrument and methane unit, seal cracks, install alarm and a fan, monitor daily, notify Health Department and Fire Department
5,000 ppm and up in atmosphere	Evacuate, call 911
10,000 ppm and up in wall or small confined places	Evacuate, call 911
40,000 ppm and up	Point source, evacuate, call 911

A 5,000-ppm (10% LEL) methane evacuation limit, consistent with the US National Fire Code criterion, was recommended. The committee considered this level to provide a sufficient factor of safety (ten times lower than the methane LEL), but also high enough if measured in mid-air to be

indicative of potentially significant concentrations in enclosed areas of the buildings (i.e., bathrooms, crawl spaces, wall spaces, storage rooms, etc.). On such occasions, the Health Department (during business hours) or the Fire Department (after business hours) was called. The inspector at the site would explain the circumstances and the Departments would make a decision if evacuation was required or not. The evacuated properties could only be re-occupied after methane levels dropped to 1,000 ppm for at least a two-week period during which the atmospheric pressure dropped to 100.9 kPa or below on at least two occasions, measured at the point(s) where highest methane readings were observed. Methane readings were to be taken when the atmospheric pressure was at or below 100.9 kPa. Affected homes had to undergo further monitoring for methane as long as the highest concentrations measured in the building dropped to or below 100 ppm over at least a two-week period under atmospheric and monitoring conditions as above.

This program was a case-specific program developed on an ad-hoc basis and has never been adopted as an official guideline or even guidance document by any of the Washington State or King County departments. However, following the Midway Landfill incident, the Washington Department of Ecology has established a limit of 100 ppm methane or less, that landfill owners must achieve in off-site structures.

2.3.2 Recommended Indoor Air Criterion

Most of the action criteria discussed above have been developed by the application of a "safety factor" approach, in which the jurisdiction assumed a factor that appeared to give a comfortable margin of safety relative to the explosion hazard.

British Columbia, Quebec and US EPA regulations specify a limit of 12,500 ppm (25% LEL), Ontario MOE uses a limit of 10,000 ppm (20% LEL), and the U.S. National Fire Code specifies a limit of 5,000 ppm (10% LEL) for methane gas in on-site buildings.

Existing limits for methane in off-site buildings vary widely between jurisdictions. For example, U.S. federal regulations and most of the state regulations (except for Washington State) do not specify a limit for indoor methane in offsite structures. British Columbia and Quebec use a limit of 12,500 ppm (25% LEL), and the U.S. National Fire Code specifies a limit of 5,000 ppm (10% LEL). The City of Winnipeg established two significant action levels: (1) methane concentration at or above 2,500 ppm (5% LEL) is an alarm level at which a series of actions can be taken at the discretion of the responsible City departments, and (2) methane concentration at or above 10,000 ppm (20% LEL) is a level at which gas mitigation measures need to be implemented (Ref. 1). All these limits are far above the normal background concentrations for methane (typically, about 2 ppm), and represent concentrations that could rapidly increase to explosive levels if gases continue to vent into the structure.

Some other jurisdictions, such as the Province of Ontario and Washington State use far more protective limits. The Washington State solid waste management regulation sets the limit for methane concentration in off-site structures at 100 ppm (Ref. 4), and the Ontario regulations state that methane gas "shall not be present" in offsite structures, implying a zero concentration limit.

Consequently, the most conservative safety factors that have been adopted by one or more jurisdictions have been assumed for the criteria recommended below:

- The recommended criterion for methane in on-site structures is 5,000 ppm (10% LEL)
- The recommended criterion for methane in off-site structures is 100 ppm .

Although the 100-ppm limit is an extremely low concentration compared to the lower explosive limit (50,000 ppm), it is high enough to be distinguished from typical background methane concentrations. This means that when methane is detected at concentrations in the 100-ppm range, further investigation is required to confirm its presence and to identify its source. Knowledge of site-specific factors including the types of activities carried out in the building is important, particularly when investigating commercial and industrial buildings. Methane levels in the 100-ppm range could be a result of a specific process or activity carried out at the property, rather than landfill gas migration. The 100-ppm criterion is regarded as the minimum concentration at which action on methane should be initiated. Higher concentrations will require more rigorous action. Chapter 10 describes a complete set of action level criteria for the management of methane in off-site buildings and soils.

2.4 Point-of-Entry Methane Concentration

2.4.1 Summary of Background Information

The City of Winnipeg was the only jurisdiction identified in the course of this study that set a limit for the point-of-entry concentration in buildings near landfills. The City identified a methane concentration of 10,000 ppm (20% LEL) as a level that requires implementation of measures to mitigate methane infiltration, provided this concentration is encountered consistently at any point source within a building. A point source is defined as a measurement obtained at a floor crack, floor joint, floor drain, column base, utility access penetration, base grade crack or pile base. To encounter a certain concentration "consistently" would mean that that concentration has been exceeded in a majority of monthly methane gas measurements over a period of one year (Ref. 1).

2.4.2 Recommended Point of Entry Criterion

Most standards reviewed, with exception of the City of Winnipeg, did not contain point of entry concentration standards separate from the indoor air concentration standards.

Because gas entering an enclosed structure from a landfill may be forced into the structure by a significant pressure gradient, any gas concentration detected within the structure at the point of entry may quickly become present in a large volume of the enclosed space. In addition, a significant (i.e., above background) point-of-entry concentration implies a potentially significant concentration and pressure outside the building which should be investigated. Therefore the point of entry concentration limits should be the same as the indoor air limits. The recommended point-of-entry levels are as follows:

- 5,000 ppm (10% LEL) for on-site buildings (same as indoor air criterion, to avoid build-up of higher concentrations).
- 100 ppm by volume for off-site buildings.

Depending on the nature of the point-of-entry, its accessibility for monitoring, and its potential for gas accumulation, rapid dilution of entering gas may occur, reducing a high external concentration to a fairly low point-of-entry concentration. For example, the City of Calgary has observed at one of their monitoring locations point-of-entry concentrations in the range of 500 – 700 ppm and soil concentrations at the side of the building close to LEL. Consequently, the selection of the 100 ppm point-of-entry limit is considered to offer some margin of safety relative to external soil concentration.

Also, atmospheric conditions may influence the point-of-entry concentration, depending on the soil methane pressure driving the gas into the building. Clearly, low gas pressures will be affected more by changing atmospheric pressure, resulting in greater variability of observed concentrations.

In the context of Alberta's surficial geology, gas migration will occur more readily in sand/gravel soils, and at lower soil methane pressures than through clays. Consequently, relatively high rates of methane migration may be possible at low pressures and relatively low point-of-entry concentrations, if the point of entry is a crack in concrete or improperly sealed joint in a sewer pipe. (See also Section 5.3 on Effects of Barometric Pressure).

Chapter 10 provides a full description of action level criteria for methane at the point-of-entry into off-site buildings.

2.5 Soil Methane Concentration Adjacent to Buildings

2.5.1 Summary of Background Information

The reviewed literature indicates that some jurisdictions use the same criterion for methane in soil adjacent to buildings as for the ambient air, while some others have developed separate sets of standards for " soils adjacent to buildings". In addition, several jurisdictions have established soil gas limits at the landfill property boundary and beyond.

British Columbia, Quebec and USEPA regulations require that landfill owners control methane in soil gas so that it does not exceed the LEL (50,000ppm) at the property boundary.

Ontario regulations require that landfill owners control methane in soil gas to achieve the following criteria:

- Methane concentration below the surface of the soil at the boundary of the site should not exceed 50,000 ppm (100% LEL)
- Methane gas concentration in soil immediately outside the foundation of an on-site building that is accessible by any person or contains electrical equipment or potential source of ignition, should not exceed 10,000 ppm (20% LEL)
- Methane gas should not be present in soil immediately outside the foundation of an off-site building that is accessible by any person or contains electrical equipment or potential source of ignition (Ref. 5).

2.5.2 Recommended Soil Methane Criterion

It is recommend that criteria for soil methane concentrations adjacent to buildings include both the soil gas pressure and the concentration of methane. The rationale for this recommendation is as follows. Due to the minimal mixing that occurs in soil pore spaces, methane concentrations in the soil can be expected to be much higher than the concentrations that will result when the gas vents from the soil and mixes with air. As a result, much higher concentrations of methane can be tolerated in the soil adjacent to buildings than in the buildings themselves.

However, when monitoring for methane adjacent to buildings, it is important to consider the pressure of the gas in the soil pore space, in addition to methane concentration. The rate at which gas can

move from the soil into the building is controlled by the soil gas pressure. Furthermore, detection of measurable soil gas pressures adjacent to a building suggests that a significant flux of gas through the soil from the landfill may be occurring. In this case, the gas concentrations may change quickly as the gas plume moves toward the building. Gas pressure measurement is included in very few standards, but is critical in controlling the rate of gas migration. Therefore, some consideration should be given to including monitoring of gas pressure when evaluating the need for controls (See Section 3.2.4 for more detail on gas pressure measurement). The literature indicates that negligible gas flows occur if the gas pressure in the soil is less than 0.249 kPa, and that at pressures above 0.249 kPa the gas flows become significant (Ref. 6).

Therefore, we recommend that the following criteria be considered for soils adjacent to buildings:

- Methane concentration of 50,000 ppm (100% LEL), if the soil gas pressure is less than 0.249 kPa (there will likely be little if any gas flow, and dilution of the gas will occur rapidly);
- Methane concentration of 5,000 ppm (10% LEL) if the pressure is 0.249 kPa greater (significant gas flows can occur, and dilution may not be sufficient to mitigate the potential explosion hazard).

3. Methane Measurements

3.1 Methods and Rationale in Existing Guidelines and Legislation

A review of the Canadian, U.S. and United Kingdom legislation and related literature was conducted to identify landfill gas monitoring methods. The following sources and documents were investigated:

- The Waste Management Board, United Kingdom
- Ministry of Environment and Energy, Ontario
- Environmental Protection Agency, US
- Solid and Hazardous Waste Management Regulations, California
- Regulations for the Solid Waste Management Board, New Jersey

The regulatory review indicated that most regulations provide descriptions of different methane monitoring methods that could be used at landfill sites, but that they do not prescribe a single or best method since each landfill has different characteristics that must be considered.

A common element that was found in all of the guidelines is the need for qualified personnel to design the gas-monitoring network based on site characteristics. All monitoring results must be recorded and records kept by the proper authority in the district and by the landowner. Specialist advice is also recommended on sampling frequency and interpretation of results. In addition, it is recommended that trained personnel perform all monitoring. Once selected, the monitoring system must be capable of detecting any possible gas migration.

3.1.1 Monitoring Locations and Frequency

Although a specific monitoring method was not identified by any of the jurisdictions, with the exception of the Ontario Ministry of Environment and Energy, all outlined how often monitoring should occur. Some jurisdictions also indicated the minimum spacing permitted between monitoring points.

Monitoring frequencies at a site should be varied under certain conditions, such as changes in gas quantity or quality, building development on or adjacent to the site and climatic changes. However, the regulations recommend that the monitoring intervals should never exceed one year. Again, it is the responsibility of the registered engineer to increase or decrease the monitoring frequency, as is deemed necessary.

The following requirements apply to monitoring frequency in the respective jurisdictions:

Ontario: No specifics presented

United Kingdom: Monitoring within the waste must continue until the flammable gas production has fallen below the level where it constitutes a risk, below 10,000 ppm (20% LEL) over a 24 month period, measured on at least 4 separate occasions.

USEPA:

For air emissions monitoring: Surface concentrations in the landfill must be monitored on a quarterly basis using an organic vapour analyser, flame ionisation detector, or other portable HC monitor according to the following:

- Measured within 5 to 10 cm of the landfill surface.
- When methane surface concentrations are below the maximum of 12,500 ppm (25% LEL), for 3 consecutive quarters, then the landfill owner may take measurements annually.
- Nitrogen, oxygen, temperature and landfill gas pressure must be monitored each month.

For soil gas monitoring at the perimeter of the landfill: The number and location of gas probes is site-specific and dependent on subsurface conditions, land use, and location and design of facility structures. Required monitoring frequency is quarterly.

New Jersey: Methane gas survey shall be performed on a quarterly basis around the perimeters of the buffer zone, and the maximum interval between sampling points should be 100 metres (300 feet).

- Maximum interval between sampling points for structures shall be 15 m (50 feet), with at least one sampling point along each side of the structure.
- Minimum sampling depth is 1 metre (3 feet) below the ground surface or above the water table, whichever is higher.

The California Integrated Waste Management Board (CIWMB) - At a minimum, quarterly monitoring is required.

USEPA & CIWMB – The lateral spacing between adjacent monitoring wells shall not exceed 305 m (1,000 feet), unless it can be established to the satisfaction of the environmental agency.

3.2 Methods Up-date

Generally there are three gas-monitoring techniques used to measure methane concentrations:

- Surface monitoring
- Sub-surface monitoring
- Underground monitoring

3.2.1 Surface - monitoring methods

Surface methane is generally monitored in two ways, either by using a portable meter in the field or by collecting samples and analysing them in the laboratory.

There are many types of portable instruments available for landfill gas monitoring. They should be regularly calibrated and serviced according to manufacturer's instructions. The following is a description of portable monitoring devices that can be used to measure surface methane concentrations:

1. **Catalytic Oxidation Detectors**

   - Favourable instrument if methane concentrations are less than the LEL
   - Measured as a percentage of the LEL
   - Must be calibrated regularly to methane

- Require oxygen in excess of 12% by volume to ensure complete oxidation
- Disadvantage: chlorinated vapours may cause a catalytic reaction, indicating a flammable gas is present even if it is not

2. Thermal Conductivity Detectors

- Measures the total concentration of all flammable gases in the sample, by comparing the thermal conductivity of the sample against an internal electronic standard representing air
- Recommended for high methane concentrations, and measured in terms of percent volume
- Must be calibrated regularly, as it can be damaged by other gases
- Disadvantage: mixture of CH_4 and CO_2 can cause inaccuracies, and therefore not an optimum for landfill gas, since landfill gas is a mixture of up to 50% CO_2 in methane
- Binary gas analyser can be utilised to correct for these inaccuracies by taking 2 measurements, one for the landfill gas, the second for the same gas with the CO_2 removed with an absorbing filter; the concentration can then be calculated

3. Combined Catalytic and Thermal Conductivity Detectors

- Battery-powered, hand-held meters, which have both catalytic oxidation and thermal conductivity devices
- Sample gas must be drawn in a continuous stream
- Disadvantage: can be contaminated by gases such as hydrogen sulphide (H_2S) and organic lead compounds

4. Flame Ionization Instruments

- Detect low concentrations of flammable gas present (zero to 10,000 ppm).
- Drawn through a hydrogen flame, at soil surfaces, soil gas and in buildings, structures and confined spaces.
- Not recommended for use when flammable gas concentrations are high
- Sufficient amount of oxygen must be present
- Disadvantage: accuracy affected by the presence of other gases, such as H_2, CO_2, water vapour and some minor components of landfill gas

5. Infrared Gas Analysers

- An infrared beam is projected through the gas sample and the amount of light absorbed at various wavelengths is measured, correlating to the concentration of methane present
- Capable in the range from 0.5 - 100 ppm, output reading as percent methane and LEL
- Recommended for detecting gases in large void spaces, such as buildings, under floors, manholes and other confined spaces
- High accuracy, self calibrating

- Disadvantage: greater power requirements, expensive, and mostly stationary models

Due to some of the inherent limitations in each type of instrument, the jurisdictions also recommend analysing surface methane concentrations in the laboratory, to verify the results obtained in the field. Additional samples should be taken, and as a result, great care and training is required to guarantee an accurate sample of landfill gas is obtained before it is analysed. Three basic delivery systems are available for obtaining a landfill gas sample:

1. **Hand Aspirator**
   - Inexpensive and recommended for obtaining small volumes of gas
   - Disadvantages: lack of flow control, and contamination from outside air sources is possible
2. **Personal Pumps**
   - Portable, hand-held pumps for gas sample collection
3. **Vacuum Pumps**
   - Advantages include large sample flow rates, sturdy construction and a low potential for air contamination

Once the sample has been collected methane concentrations can be measured using:

1. **Gas Chromatography (GC)**
   - Available as portable instruments for instantaneous measurements
   - Most reliable method, accurate, repeatable, low detection limit
   - Recommend a permanent GC, to confirm measurements taken by portable equipment
2. **Mass Spectrometer**
   - Can be combined with GC to analyze for trace components
   - Advantage: conclusive compound identification
   - Disadvantage: expensive

3.2.2 Sub-surface Monitoring with Temporary Probes

Probes driven into the potential areas of concern provide point source monitoring of methane gas concentrations in the local environment around the probe. These probes are only suitable for measuring methane concentrations near the surface, as they can only be driven approximately one to two metres into the soil. The gas probes consist of metal tapered tips, coupled firstly to short steel or plastic perforated pipe, and then to longer un-perforated metal pipes. Examples of sub-surface probes, with steel and plastic piping are illustrated in Figure 3-1. Again, it is the responsibility of a qualified professional to determine the type of probe, and its location and depth.

3.2.3 Underground Monitoring with Permanent Wells or Probes

The best method to monitor methane gas underground is by installing gas monitoring boreholes, or wells. Permanent wells or probes consist of perforated plastic casing adjacent to the strata, with

probes or tubes permanently installed within the casing. To obtain more representative data, multiple point monitoring wells can be installed, where discrete sampling probes are placed at set intervals within the wells. Both simple and multiple point monitoring wells are illustrated in Figure 3-2. Information on gas production can be obtained from wells drilled within the wastes, and the gas migration potential can be determined from sampling locations outside the site. Qualified personnel should determine the location of the wells.

3.2.4 Gas Pressure Measurements

The USEPA recommends that the gas pressure gradient should be monitored to verify methane migration potential. Gas pressure can be monitored along with gas composition by using a gas monitoring well installation similar to that of a water well. Typically, a gas pressure monitoring well will use 0.5" or 0.75" PVC tubing with screens and bentonite seals, and a valve and hose fitting for connecting the monitoring instruments at the top of the well (Figure 3-3).

Gas pressure measurements can be taken readily with one of the following instruments:

1. **U-tube manometer**

   - Consists of a u-shaped tube filled about halfway with fluid (water or mercury), with both ends open to the atmosphere and the fluid at the same height in both tubes (zero point). Application of positive or negative pressure (when connected to a monitoring well or a probe) at one end of the tube will result in a change in the fluid level, with the total difference in fluid level representing the pressure

   - Can be used to measure positive, negative or differential pressure in a monitoring well or LFG collection system piping

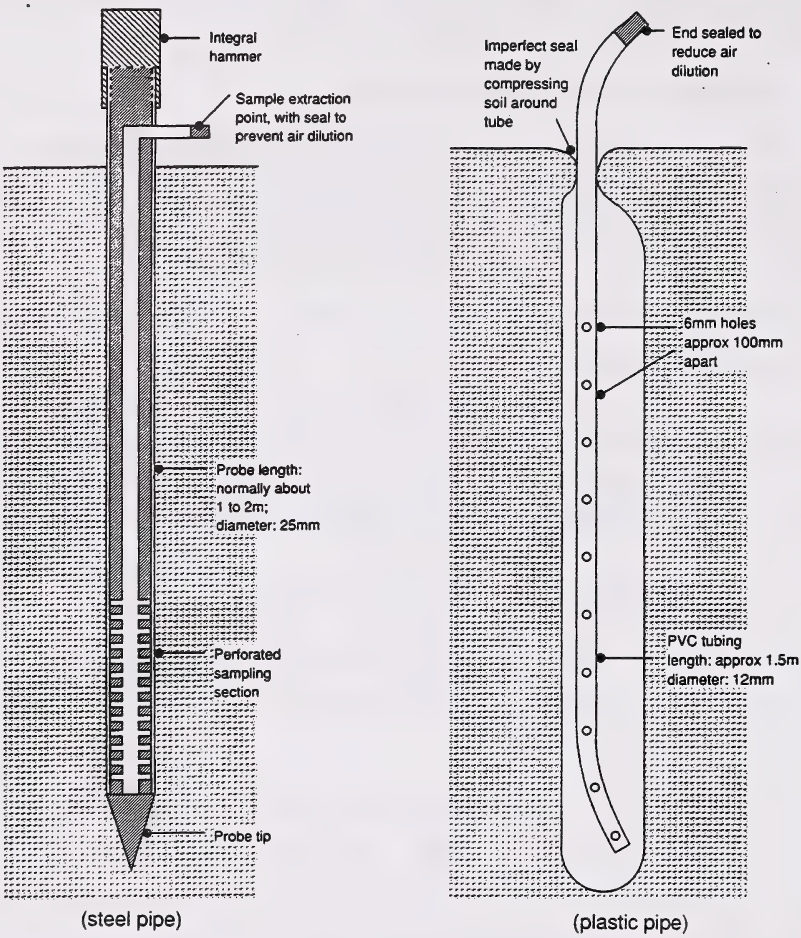


Figure 3-1
Sub-Surface Monitoring Probes

CGY/98/203C/25804/999F4.CDR

CG&S
CH2M Gore & Storrie Limited

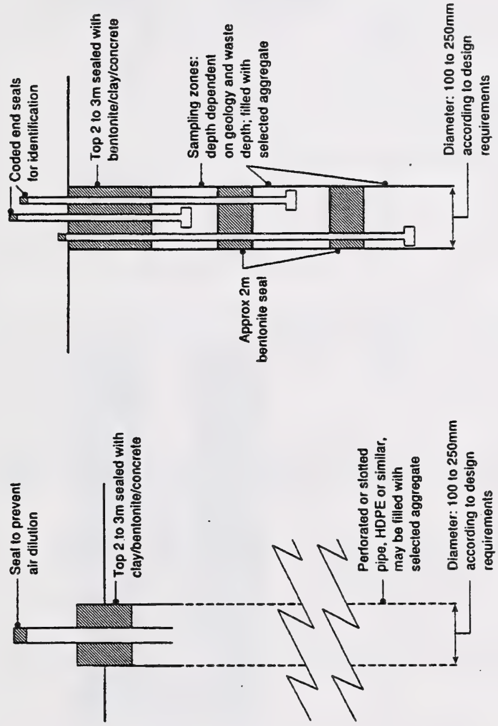


Figure 3-2
Underground Monitoring Boreholes

CG&S
CH2M Gore & Storrie Limited

CGY/98/203C/25804/999F4.CDR

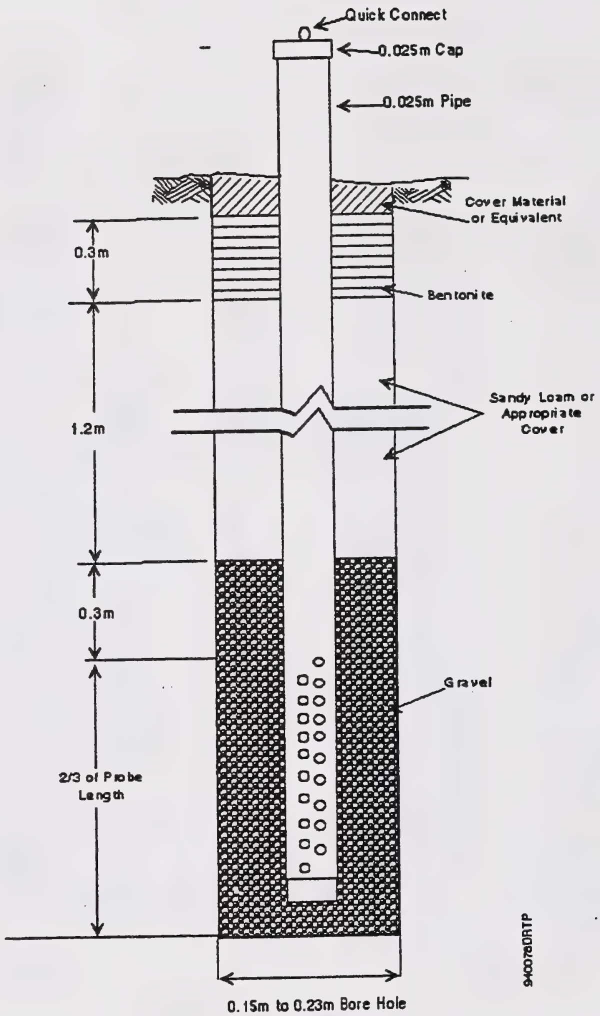


Figure 3-3
Pressure Probe

CGY/98/203C/25804/999F4.CDR

CG&S
CH2M Gore & Storrie Limited

- Advantages: high accuracy, no power source needed, one port measures both positive and negative pressure, provides direct measurement of pressure, capable of measurements over the full range of pressures expected
- Disadvantages: potential loss of fluid (water or mercury) during transport, must be held vertically and must be secured when in use, must have a scale that covers needed range; fluid density must be appropriate to expected pressure range

2. Magnahelic pressure gauge

- Magnahelic (trade name) pressure gauge is a small, hand-held instrument that senses the change in gas pressure through the use of an internal diaphragm
- Can be used to measure both positive and negative pressure in a gas monitoring well, a probe or LFG collection system piping
- Separate gauges are available for different ranges of gas pressure (e.g., 0 – 0.1245 kPa, 0 – 1.245 kPa, and 0 – 19.92 kPa)
- Advantages: highly responsive (accurate within 2% of full scale, resistant to shock and vibration, no liquid involved, small and portable
- Disadvantages: separate gauges needed to accommodate a wide range of pressures, each port measures only positive or negative pressure, gauges must be in a vertical position for accurate measurement

3. Electronic pressure gauge

- Electronic pressure gauges use a pressure transducer to measure the pressure at the inlet port
- Can be used to measure positive, negative or differential pressure
- Available in ranges from 0 – 250 kPa, accurate to within 2% of full scale
- Advantages: high accuracy, no levelling of the instrument required, no fluid involved, adjustable scale (one instrument appropriate for all pressure ranges)
- Disadvantages: requires a power source, LCD readout can be problematic in extreme cold.

3.2.5 Methods

Three suppliers, GasTech Instruments Canada Ltd., Inventus Technologies, and Landfill Control Technologies, were contacted to identify the preferred methods of methane detection in landfill gas.

GasTech Instruments recommended the use of a dual sensor instrument to test for methane and other gases in landfills, trenches and other applications. The monitor consists of two sensors, a catalytic oxidation sensor and a thermal conductivity sensor. At low concentrations, the catalytic sensor is active, and as the methane concentration increases, the monitor automatically switches to the thermal conductivity sensor. This enables the instrument to detect methane at any concentration, as a percentage of LEL or a percentage of volume (or ppm), respectively. In addition, the monitor is capable of taking simultaneous measurements of methane, oxygen and carbon dioxide. It can be used for instantaneous and continuous methane measurements, as it has data-logging capabilities.

Inventus Technologies is currently planning on utilising a High Speed Hydrocarbon Detector, that has been designed on surveys of Transmission Gas Pipelines, to detect methane in landfill gas. The instrument utilises "Open Path" Infrared Technology, where an infrared light is directed to an open-air path to the detector unit, which produces an electrical voltage output proportional to the intensity of the light. A reference channel is used to detect light at a wavelength not absorbed by any of the gases of interest. Then, an absorbance value is calculated for the gas of interest, based on the difference between the intensities measured by the reference and gas detectors. Inventus Technologies claim that this method is favoured over flame ionization detection because it is quicker, more sensitive, and allows for the simultaneous measurement of methane, carbon dioxide and total hydrocarbons. The instrument displays the data graphically, in real-time, producing instantaneous methane measurements.

A third gas detection technology is commonly used in the U.S. for gas monitoring at landfills. An integrated gas sampling meter is produced by at least two manufacturers (Landfill Control Technologies and LFG&E, both in California). The integrated meters contain closed—path infrared gas measurement devices that analyze a gas sample aspirated into the meter through an internal pump. The meters measure both methane and oxygen as well as carbon dioxide in the gas stream. The meters also measure gas pressure.

3.3 Recommended Monitoring Methods

On properties adjacent to a sanitary landfill containing decomposable organic material, a subsurface monitoring program should be developed to detect combustible gas that may have migrated or may migrate in the future from the landfill. The design and location of subsurface monitoring wells should be based on a thorough understanding of the nature of the soils in the vicinity of the landfill and the subject property, including the soil strata present, the location of the water table, and the permeability of the soils to gas flow. The monitoring program should include a definition of preferential pathways of gas flow from the landfill, including permeable strata and man-made pathways such as utility conduit backfill.

The choice of a monitoring method is site-specific, and can only be made once all of the landfill characteristics and the properties of the adjacent land have been considered. A qualified professional experienced in landfill gas control and monitoring should complete the analysis. For surface monitoring, the following monitoring methods are available:

1. Catalytic Oxidation Detectors
2. Thermal Conductivity Detectors
3. Combined Catalytic and Thermal Conductivity Detectors
4. Flame Ionisation Instruments
5. Infrared Gas Analysers

Permanent gas monitoring wells or probes are recommended for soil gas monitoring. Temporary driven (often referred to as "bar-hole") probes may be considered for shallow sub-surface gas monitoring to determine the extent of a subsurface gas plume and as a screen to guide the installation of permanent probes or wells.

3.4 Methane alarms

Gas monitoring alarms are installed in buildings and foundations spaces to notify tenants and landowners that the concentration of methane has exceeded its acceptable limit.

Various suppliers sell gas monitoring alarms for landfill sites and buildings. Manufacturers provide single point and multiple point gas sensors, designed for permanent installation to monitor flammable gas, toxic gas or oxygen deficiency in buildings and on landfill sites. The units can be flush, panel or surface mounted, and therefore are suitable for space restricted areas. Digital displays give precise indication of gas levels, in terms of LEL with 2% accuracy, as well as alarm set points. Regular calibration is necessary and can be performed with a hand-held device.

The primary concern with gas monitoring alarms is their maintenance. Once installed, the monitors must be regularly inspected and calibrated to ensure they are working properly and accurately. As they can also detect hydrocarbons other than methane that are not harmful, they may cause false alarms on occasion. Methane alarms are a useful tool, but require routine maintenance.

4. Other Methane Sources

As a product of anaerobic decomposition of organic materials, methane is one of the components found in gas mixtures originating from a number of man-made and naturally occurring sources including sewer gas, landfill gas, natural gas, and swamp gas. Since all of these gases are generated by the same biological processes and under similar conditions, they all contain some of the same components, namely, methane, carbon dioxide, and hydrogen sulfide. However, depending on the source, the proportion of these components will vary, as will the types and amounts of trace constituents. As a result, it may be possible to identify the likely source of gas based on its composition, i.e., types and concentrations of major and minor components.

4.1 Sewer Gas

Sewer gases containing methane are formed by the same microbial processes that form landfill gas. The methane and carbon dioxide concentrations in sewer gas and the carbon 14 content are therefore similar to landfill gas (Ref. 7).

However, as the waste materials that make up sewage typically have less varied composition than the waste materials in a landfill, the trace components are typically less variable than in landfill gas (Ref. 10). Chlorinated compounds are not commonly found in measurable concentrations in sewer gases. However, gases formed in some landfills also have very low concentrations of chlorinated and other volatile organic compounds. Knowledge of site specific conditions is frequently essential to differentiating sewer gas from landfill gas.

4.2 Natural Gas (Pipeline Gas)

Natural gas is composed primarily of methane, ethane and other hydrocarbons containing one to four carbons and sometimes higher molecular weight species (Ref. 11). Unlike landfill gas, natural gas does not contain carbon dioxide. Landfill gas, because of its microbial origin, does not contain significant concentrations of hydrocarbons other than methane. Therefore, the presence of significant levels of ethane and higher gaseous hydrocarbons is an indication of natural (pipeline) gas (Ref. 6). As well, natural (pipeline) gas usually contains an odorant or "flavouring" agent such as a mercaptan, to allow for olfactory detection at concentrations well below the LEL.

Natural gas is typically obtained from deep deposits of ancient gas and therefore contains no carbon 14 (Ref. 7), and can be differentiated from landfill gas by isotope analysis.

4.3 Gas from Natural Sources

Swamp gas is formed from the anaerobic decomposition of recently deposited organic materials, similar to landfill gas, but because of the nature of the organic materials typically contains no measurable chlorinated organic compounds.

"Drift gas" is gas formed by organic material that was buried during glaciation or glacial retreat, and so is associated with the soil materials known as glacial drift. The buried organic material is much

older than landfill waste and can be expected to be depleted in carbon 14 relative to atmospheric concentrations (Ref. 7).

4.4 Other Factors in Source Characterization

Sometimes, comparison of relative concentrations of volatile organic compounds in the gas measured at different locations can suggest a common source. The source of methane migration from a landfill is best defined by determining and tracing the pathway of migration, using gas sampling probes.

5. Gas Migration and Seasonal Variations

5.1 Gas Migration

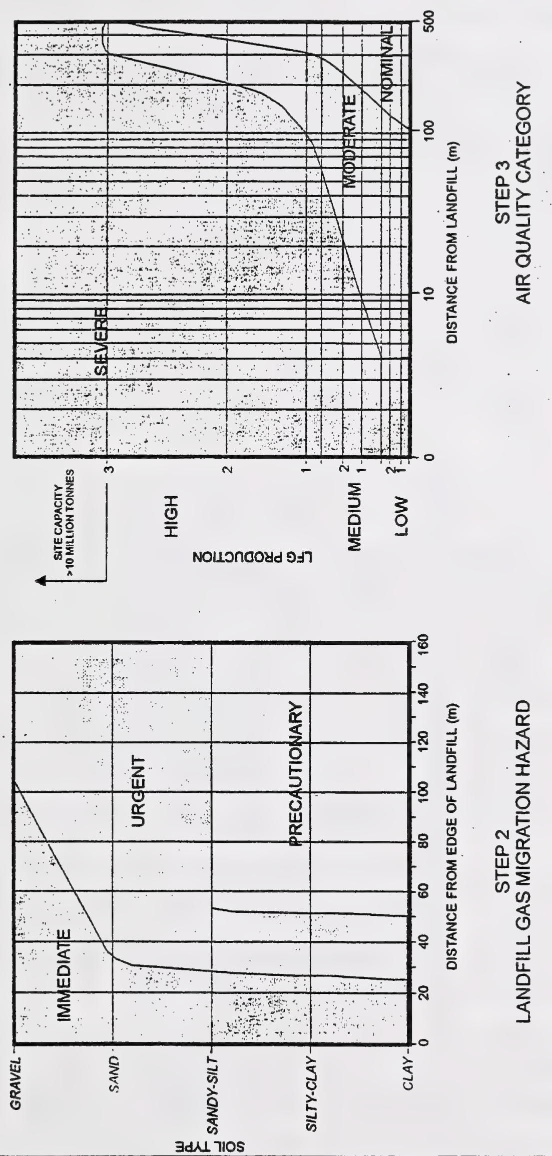
The migration of gases through the soil is a result of two processes: diffusion in response to a concentration gradient, and convection, due to a pressure gradient. Under ideal conditions, the gas moves preferentially along paths of lowest resistance and is eventually discharged to the atmosphere. This means that the gas will move by diffusion in the direction of decreasing concentration, and by convection in the direction of decreasing pressure.

The primary factors that influence the distance gas migrates from the landfill are the permeability of the soil adjacent to the landfill, and the type of ground surface cover around the landfill. Generally, the greater the permeability of the soil, the greater the possible gas migration distance. As methane is lighter than air, it tends to rise and escape preferentially through the landfill cover, whenever the cover is sufficiently permeable.

Lateral migration of methane is enhanced if higher-permeability soils such as sand and gravel, or fractured till are present adjacent to the landfill. This is of particular interest in Alberta. Most of Alberta has been affected by glacial activity, which has resulted in a layer of till material being deposited on the land surface. Till is a mixture of poorly sorted sediments ranging in size from clays to gravel and boulders. Poorly sorted sediments and deep fractures within the uppermost 30 metres of the clay till are present in many areas of the province. Consequently, thorough knowledge of local geological features at a specific site of interest is important, as presence of heterogenous soils or fractured till around the site can result in increased permeability and increased rate of methane migration.

Man-made structures containing granular fill such as sanitary sewers, utility trenches and storm and foundation drains are important as they may provide preferential pathways for gas migration. Also, additional factors, such as the soil surface cover (snow, ice, pavement), the elevation of the groundwater table, and the existence of barriers or vents along the migration pathways may affect the direction and extent of the gas migration.

Figure 5-1 shows LFG migration hazard charts presented in Environment Canada 's "Guidance Document for Landfill Gas Management". The charts correlate the degree of gas migration hazard with the type of soil surrounding the landfill and the distance from the edge of the landfill to the nearest structure. The LFG migration hazard is defined as "immediate", "urgent" and "precautionary", and Environment Canada recommends that action to be taken should be in accordance with the level of urgency conveyed by these terms. The figure also shows a correlation between severity of concerns regarding air quality and the estimated gas production and distance between the landfill and the nearest property.



NOTES:

1. ASSUMES 4 MONTHS/YEAR OF FROZEN GROUND AND DRY SOIL CONDITIONS
2. IF HETEROGENEOUS SOILS ARE PRESENT ASSUME THE NEXT HIGHER CATEGORY
3. FOR FRACTURED ROCK STRATA ASSUME EQUIVALENT TO GRAVEL

Source:

Environment Canada, 1996

203C/25804/999FG.CDR

Figure 5-1
LFG Migration Hazard Chart

CG&S
CH2M Gore & Storrie Limited

5.2 Effects of Temperature

Changes in ambient temperature are important as they affect both the rate at which methane and other landfill gases are generated, and the rate at which they migrate through the soil.

The optimum temperature range for the maximum rate of landfill gas generation is between 35 and 45°C, which means that higher ambient temperatures will result in increased gas production. A dramatic drop in gas production occurs below 10 to 15°C. However, temperatures within landfills typically are higher than the ambient temperature due to the biological decomposition process, which generates heat. Therefore, the temperature within a landfill (which can be measured indirectly by measuring the temperature of a gas stream exiting the landfill) is a much more important indicator of gas generation potential than the ambient temperature (Ref. 12).

Generally, increases in ambient temperature result in increased rates of gas migration, as it enhances the diffusion of the gas through the soil. However, phenomena like snow cover or frozen soil have a more profound effect on methane gas migration than the ambient temperature itself. This is particularly true in Alberta, where frost can last from late October until the end of June (Ref. 13). As an illustration, Table 5-1 shows historic average daily temperatures for a number of towns across Alberta.

Snow or frost cover can effectively seal the surface of the soil preventing methane from venting to the atmosphere. This may result in pressure build-up within the landfill and significant increase in lateral migration of the gas along the subsurface paths of least resistance until it finds a vertical path to the atmosphere. Data on frost penetration depths for various places in Alberta are not readily available, as they are very site-specific, and depend on a number of factors, such as soil particle size, moisture content and thermal conductivity, and atmospheric conditions (air temperature, wind conditions and duration of the freezing period). However, it can be expected that the depth of frost penetration will likely vary from about 1.5 metres in southern Alberta to about 3 metres or more in northern parts of the province. Generally, the depth of frost penetration will be greater in coarse-grained soils, and in zones where there is little water which must be converted to ice. This means that frost will penetrate to greater depths in sandy soils than in wet clay till. On the other hand, snow cover acts as insulation, and will result in lower frost depth.

In the winter, building foundations can act as preferential conduits for methane gas migration, since they penetrate the frost layer. Migration may occur into the building, through foundation drains, or through an unfrozen layer around the foundation caused by the heat from the foundation. Consequently, methane concentrations inside a building may vary substantially on a seasonal basis, particularly when the building foundation is set in permeable soil.

To account for seasonal temperature changes and effects associated with snow/frost cover, methane gas monitoring data should be collected at least once during each season. The observed effects will vary according to the site-specific conditions, but may include the following:

- Drop in measured methane concentrations during spring and summer, following the annual snowmelt and spring rains snowmelt.

TABLE 5-1
HISTORIC DAILY AVERAGE TEMPERATURES FOR SELECTED ALBERTA COMMUNITIES

Month	High Level	Peace River	Ft. McMurray	Grande Prairie	Edmonton	Lloydminster	Calgary	Lethbridge	Medicine Hat
January	-24.6	-20.4	-21.8	-17.7	-16.5	-18.2	-11.8	-10.3	-12.6
February	-18.5	-13.5	-15.4	-12.1	-11.4	-13.2	-7.3	-5.4	-7.7
March	-11.8	-8.5	-9.2	-7.2	-6.7	-7.9	-4	-2.1	-2.8
April	0.8	2.1	2.1	2.7	3.2	2.9	3.3	4.9	5.6
May	9.3	9.6	9.7	10	10.1	10.8	9.4	11	12.3
June	13.6	13.8	14	13.7	14.1	14.9	13.5	15.4	16.6
July	15.7	15.7	16.4	15.9	15.8	17.5	16.4	18.6	19.9
August	14	14.2	14.8	14.8	14.8	16.1	15.2	17.6	18.9
September	8.1	9.1	9	9.8	9.8	10.4	10.6	12.7	13.2
October	1.3	3.7	3.3	4.2	4.7	4.4	5.5	7.5	7.4
November	-11.4	-8.1	-8.2	-6	-5.5	-5.8	-2.7	-0.8	-1.6
December	-20.3	-15.3	-17	-13.4	-13.1	-12.5	-7.8	-5.8	-7.6

Source: "Canadian Climate Normals, 1951-1980, Temperature and precipitation", Environment Canada

All temperatures in degrees Celsius

- Increase in the distance of methane migration during winter months accompanied by increase in methane concentrations in buildings and structures along the preferential migration pathways

5.3 Effects of Barometric Pressure

The processes of landfill gas generation produce the increased pressure that represents the driving force for the movement of landfill gases through the soil. The pressure differential between the landfill and the adjacent regions of lower pressure (i.e., the atmosphere or the surrounding soil) provides the driving force for migration of methane gas. Significant gas migration will occur even when the pressure difference between the landfill and the adjacent areas is as low as 0.3 kPa (0.003 atm) (Ref. 6).

Changes in barometric pressure have a significant effect on venting of the methane to the atmosphere. A decrease in barometric pressure will result in a larger pressure differential between the landfill and the atmosphere and consequently in higher flux of methane from the soil into the atmosphere. It can be expected that, in general, as the vertical migration rates increase, the lateral movement of the gas will be reduced. Conversely, increased barometric pressure will, in general, slow down the rate of vertical migration and result in either increased rate of lateral migration or accumulation of methane in the soil. In cases where the soils surrounding a landfill are highly permeable in relation to the landfill cover soil, a decrease in barometric pressure will increase lateral migration.

It is extremely important to be aware of the changes in atmospheric pressure during methane gas measurements, as slight changes in pressure, either positive or negative, can result in erroneous interpretation of results. Atmospheric conditions, both temperature and pressure, should be recorded during each methane gas measurement.

When sampling methane gas inside buildings, it is important to know if the building has a HVAC system, how the system operates, and if the system is turned on or off, as HVAC operation can affect migration of methane gas into a building. HVAC systems that operate under positive pressure would reduce influx of methane gas, and systems that operate under negative pressure (e.g., exhaust fans) would increase the influx of methane into the building. In either case, the pressure differential between indoors and outdoors, as well as the absolute pressure should be measured to allow for proper interpretation of results (e.g., the pressure differential may increase or decrease the rate of migration. Methane gas measurements should be conducted with HVAC system both on and off, to determine if methane accumulation could occur when the HVAC system is not in operation.

5.4 Other Seasonal Variations

Changes in soil moisture content profoundly affect migration of gases through the soil. Increase in soil moisture content reduces the available pore space and significantly decreases soil permeability and gas diffusion. Under saturated conditions that may occur during spring snowmelt and heavy rainfall that often occur in Alberta, lateral movement of gases through the saturated soil is virtually zero. The gas generated in a saturated zone will move rapidly to the surface of the saturated zone under buoyancy. However, if saturation conditions are confined only to the surficial soil, as may happen during rainy periods of the year, the extent of lateral migration of the methane gas may actually increase, as the gas will continue to migrate through partially saturated and unsaturated subsurface soils, i.e. without having the opportunity to vent to the atmosphere.

Groundwater represents the lower boundary to migration of methane. Methane has very low solubility in water and does not move through it. Therefore, as the water table rises, both vertical and lateral migration may be increased, provided migration pathways are available. However, a rising groundwater table may block pathways for gas migration causing an increase in gas pressure in the landfill if no migration pathways are available.

6. Land Use Planning Issues

As described in the legislation reviewed for this project, recommended land uses in the vicinity of landfills as well as separation distances between the proposed development and the landfill depend on a number of factors, such as:

- Type, size and age of the landfill (these affect the potential for methane generation or actual methane generation rates)
- Local geological and hydrogeological conditions in the area around the landfill (these affect methane gas migration pathways and rate of migration)
- Nature of the proposed development, including types of activities carried out in the building and number of hours per day that the structure will be occupied (these will be different for residential, commercial, or industrial buildings, and for hospitals, schools or restaurants)

6.1 Siting Requirements in Various Jurisdictions

Review of the existing legislation and other relevant literature as well as correspondence with provincial and municipal representatives indicated that the following siting requirements are currently in place:

Alberta: Subdivisions for schools, hospitals, food establishments and residences cannot be built with 450 m of an existing landfill or 300 m of a closed landfill (Ref.14)

British Columbia: The distance between a municipal solid waste landfill and the nearest residence, school, hotel, restaurant, food processing facility, church, water supply well, water supply intake or public parks is to be a minimum of 300 metres. Greater or lesser separation distances may be approved where justified (Ref. 15)

Ontario: No land use may take place within 30 metres of a perimeter of an operating or non-operating landfill. For operating landfills, this is a minimum distance, for non-operating landfills this distance may be reduced to 20 metres if no leachate control is required at the site.

The Ministry will normally recommend against proposal for sensitive land uses adjacent to operating landfills. Sensitive uses comprise the following:

- a permanent structure used in animal husbandry
- agricultural land used for pasturing livestock
- a permanent structure where a person sleeps or a person is present on a full-time basis,
- but do not include food or motor vehicle facilities adjacent to highways, utility operations, scrap yards, heavy industrial uses.

The Ministry will normally not permit residential or other sensitive land uses on non-operating landfills. When a development is proposed within 500 metres of a landfill, the proponent must evaluate the presence and impact of any adverse effects or risks to health and safety (Ref. 16)

City of Winnipeg: The City of Winnipeg identified three separation distances (Zones of Concern) that apply to landfill sites in Winnipeg. They are 15 m, 45 m, and 90 m. These distances were selected after the City's Solid Waste Division conducted a comprehensive evaluation of 35 landfill sites (1 active, 34 inactive) located within city limits. The evaluation was conducted as a series of site investigations and modelling studies with respect to methane generation and migration potential, leachate generation and migration potential, and existing adjacent land uses for each site. This, so called, Landfill Environmental Program lasted from 1979 until 1984. Based on the results of the evaluation, a specific separation distance or distances were selected for each landfill site.

The current interim policy regarding land development within the Zone of Concerns adjacent to landfill sites, indicates that a building permit within the Zone of Concern will be granted only when results of appropriate tests indicate that there does not appear to be a significant amount of gas in the area of proposed development, or when acceptable safety measures are incorporated when test results indicate that significant amounts of gas are reaching the permit area. If the City's monitoring program is not in place at the particular site, the owner must install and maintain for up to three years acceptable gas test probes and must grant the City access for testing (Ref. 17).

The policy does not specify what a "significant" level of gas is, but, in practice, a level greater than or equal to 10,000 ppm (20% LEL) in the subsurface in the control zone is considered significant and would require building control measures. If levels are less than 20% LEL, an evaluation on a site-specific basis must be conducted, based on the City's historical monitoring data for the given site. The action level of 20% LEL was selected by the City to provide a safety factor of 5 compared to the LEL.

Types of land use allowed within the Zones of Concern are determined on a site-specific basis, and can include any use (i.e., residential, commercial or industrial), provided that the criteria set in the guideline are met (Ref.1).

6.2 Recommendations for Commercial Buildings

No policies specific to commercial developments near landfill sites were found in any of the reviewed documents. As well, discussions with a number of Canadian municipalities indicated that development permits, including ones for commercial purposes, are evaluated on site- and case-specific basis. Most municipalities indicated that they are not considering developing specific guidelines regarding land development at this time.

No stated rationale for the difference in treatment between commercial and other uses, was found in any of the legislation or literature reviewed. The differences may be based qualitatively in the concept of reduced exposure or reduced risk because of limited occupancy or reduced sensitivity of the occupants of most commercial buildings relative to sensitive uses; that is, exposure in a commercial building is likely to be a maximum of 8 to 10 hours per person, per day (i.e., typical shift length), and therefore there is reduced risk of exposure to methane, to explosion hazard, or to other potentially hazardous conditions (e.g. contaminants).

Although this study deals specifically with issues related to migration and management of methane gas, there is a potential health risk from components of landfill gas other than methane (e.g. chlorinated solvents or benzene), to which chronic part time exposure could occur over a number of years for a long term employee. One approach would be to apply the concept of risk assessment to this issue to determine if there is in fact a reduced and therefore acceptable level of risk to employees in commercial or industrial buildings to be built near landfills. The same argument could be applied

to explosion hazard, since a commercial building is no less likely to be exposed to methane gas through migration than a "sensitive use".

However, it is recommended that a more straightforward approach be used to developing criteria for different uses; an approach similar to that used by the City of Winnipeg could be considered, as follows:

- Conduct gas concentration and pressure monitoring around the landfill perimeter to establish the potential for and extent of methane migration off-site
- Set up zones for development (or no development) based on current (for closed landfills) and projected (for active landfills) soil methane concentrations not exceeding 5,000 ppm (10% LEL) or 10,000 ppm (20 % LEL)
- Exceptions might be granted if the proponent of the development is prepared to install appropriate gas control measures, as recommended by an experienced qualified professional retained by the municipality on a cost recovery basis from the proponent. However, the subdivision approving authorities should retain direct control over the use of properties and reserve the right to approve or reject development applications, as defined by the Alberta Municipal Government Act and accompanying regulations.

7. Site Mitigation, Abatement and Control

Two methods are typically employed to control landfill gas migration, passive and active systems. Passive systems depend on the pressure differential between the landfill gas and the gas collection wells and/or the atmosphere, for the gas to exit the landfill or structure. Active systems require mechanical blowers or compressors to create a negative pressure, drawing the landfill gas into the collection systems. Again, the choice and location is site-specific, and an experienced professional should be the one responsible for the decision.

7.1 Passive Systems

Passive systems rely on highly permeable material, such as gravel, placed in the path of gas flow. To control landfill gas migration, vents, barrier walls or a combination of trenches and walls are typically installed. The following is a description of these passive systems.

Vents can be installed on or around the landfill. There are two types: well vents and trench vents. Well Vents consist of 4” to 6” diameter plastic piping, usually PVC, with an interval(s) of perforation in the lower part of the pipe. The pipes are placed into drilled boreholes and extend several feet above the landfill surface. The depth of these vents is dependent on the site characteristics. Trench vents are typically installed in areas where the likely migration pathway is relatively close to the surface. A trench is excavated to a confining layer and backfilled with a porous medium, such as gravel. The gas will follow the path of least resistance and migrate up to the atmosphere after entering the porous zone (Ref. 18.)

Barrier systems are constructed outside the landfill area and extend to a low permeability bottom seal or natural barrier such as geomembranes or natural clays. The low permeability soils should be properly graded & maintained at a nearly saturated condition, to impede the convective and diffusive flow of methane gas. Dry soils are ineffective, as they include voids through which the gas can migrate (Ref. 19).

To prevent landfill gas from migrating into structures or buildings, sub-slab ventilation techniques, consisting of vents or barriers are typically employed. In this case, the vents consist of 2” to 6” PVC piping placed in gravel bedding just below the foundation, that are connected to risers that ventilate the gases above the roof. The barriers consist of flexible plastic membranes installed on top of or under the foundation to ensure that there are no landfill gas intrusion points. If the membranes are installed on top of the foundation, they must be covered with a 2 to 4” thick topping slab (Ref. 18).

7.1.2 Geomembranes and Impermeable Covers

Geomembranes are installed in barriers and trenches to prevent gas migration. Typically they consist of 20 to 60 mil thick polyvinyl chloride (PVC), chlorinated polyethylene (CPE), hypalon or high-density polyethylene (HDPE). Geomembranes must have a relatively low permeability, high resistance to puncture and tearing, and must be durable, flexible and of an inert nature.

An impermeable cover installed on a landfill site is beneficial because it prevents water infiltration, reducing the amount of methane generated, and it decreases the amount of methane gas entering the atmosphere. However, an impermeable cover may result in lateral movement of the methane, especially if there is no impermeable lining on the bottom and sideslopes of the landfill.

There are two cell covers used in landfill operations, a daily and final cell cover. The difference between the two is the frequency and thickness of application. In all of the regulations investigated, the permeability of the cover, either daily or final must be less than 10^{-5} cm/sec. The cover can be a geomembrane, however the synthetic membrane does not have to be the same type or thickness as the membrane in the bottom of the liner system (Ref. 20).

The regulations for landfill sites issued by BC Environment and the New Jersey Solid Waste Management Board specify minimum requirements for impermeable covers.

BC Environment

- The cover must have a minimum thickness of 1 metre of compacted soil, plus a minimum of 0.15 metres of topsoil with approved vegetation
- Appropriate run-on/run-off drainage and erosion controls must be installed
- Depth of final cover shall be a minimum of 18 inches

New Jersey Regulations for the Solid Waste Management Board

- The depth of the final cover must be a minimum of 18 inches, overlain by a minimum of a 6 inch erosion layer
- The synthetic membrane must have a minimum thickness of 30 mils
- If HDPE is used, minimum thickness of 60 mils is required

Alberta Environmental Protection defines final cover requirements for landfills accepting less than 10,000 t/yr of non-hazardous solid waste in the 'Code of Practice for Landfills' (Sept. 1996):

- A barrier layer of 0.60 metres of earthen material with a maximum permeability of 10^{-7} metres/sec must be included in the final cover system
- Subsoil shall be spread evenly over the barrier layer
- Salvaged topsoil shall be spread evenly over the subsoil
- Depths of soil shall be determined at the landfill site, with minimum requirements of:
    - 0.35 metres subsoil and 0.20 metres topsoil, for pasture or recreational areas
    - 0.80 metres subsoil and 0.20 metres topsoil for cultivated land use or forestry
- Minimum grade of the final cover system must be 5%, maximum of 30%.

7.2 Active Systems

In active systems, well or trench vents are equipped with an exhauster to extract gas and form a negative pressure gradient, or air is injected to form a positive pressure gradient. Air injection into

natural soils is sometimes employed in areas adjacent to landfills and can also be used to dilute gas concentrations to non-hazardous levels.

Active systems installed in structures or foundations also use sub-slab ventilation techniques with vents and/or barriers. Again, 2" to 6" PVC piping in gravel bedding is installed just below the foundation. The vents are connected to blower(s) and a vacuum is applied to extract sub-slab gases and ventilate them through a riser above the roof structure (Ref. 18).

7.2.1 Landfill Gas Utilization

Landfill gas can be captured and controlled by installing a series of interconnected perforated pipes under an impermeable cover, and directed to a main collection header. The gas can then be burned using flares, thereby decreasing the amount of greenhouse gases released to the atmosphere or utilized to generate electricity, low pressure steam, or heat.

Flares

All of the regulations investigated recommend that flares be designed to destruct 98% of the landfill gas. Typically there are two types of flares, open and enclosed. An open flare consists of an elevated stack with an open burner tip protected by a windscreen at the top. An enclosed flare consists of a chimney type stack, with the combustion tip located at the bottom of the stack. Air flow can be adjusted in an enclosed flare providing a more reliable, efficient combustion (Ref. 21).

Landfill Gas Utilization

Landfill Gas can be used for a variety of processes such as:

1. High Btu, Pipeline Quality Gas
2. Medium Btu, Industrial Fuel Gas
3. Electric Power Generation
4. Vehicle Fuel
5. Chemical Feed Stock

Prior to installing gas utilization technologies, investigations must be performed to determine if the landfills have enough waste to support a recovery project, and if it is economically feasible.

7.3 System Maintenance

Mitigation system maintenance consists of two main components, maintenance of the well-field and maintenance of the gas exhauster and flare system.

7.3.1 Well-field Maintenance

Regular inspections, at least monthly, are required to determine that the system components are functioning as intended and have not been blocked by water accumulation or damage caused by landfill settlement or other causes.

For an active exhaust system, the methane content and gas pressure (or vacuum) at each well and horizontal collector and in the main collector pipes should be tested regularly and adjusted to

maximize gas extraction while minimizing air intrusion. The frequency of monitoring and adjustment is a site-specific issue that should be addressed as part of design and adjusted during the initial year or two of operations.

7.3.2 Maintenance of the Exhauster and Flare

Exhausters are mechanical equipment that require regular maintenance including lubrication and replacement of worn moving parts. Lubrication, inspections and other regular maintenance should be done strictly in accordance with the exhauster manufacturer's recommendations. Other maintenance at exhauster/flare facilities typically includes draining condensate collection vessels (or maintaining their pumps), cleaning flame arrestors, filters, and condensate drain piping and collection vessels, and replacing thermocouples and other sensors on the flare.

7.4 Use of Specialists

Due to the site-specific nature of landfills, landfill owners must employ an experienced qualified professional to design and install a gas control system to meet the regulations issued by the province or state. Inadequate investigations in the past have produced either ineffective control measures or uneconomical over-designed systems.

Site investigations will determine whether passive or active systems are required to manage the landfill gas, and with proper analysis by a qualified professional, the correct control measures will be installed.

8. Use of Gas Generation Information

8.1 USEPA Model of Gas Generation

USEPA has published a model of gas generation in municipal solid waste landfills. This model must be used by landfill owners in the U.S. in order to comply with 1996 landfill air emission standards (Ref. 22).

The USEPA gas generation model is intended to provide a conservatively high estimate. USEPA selected an exponential decay model that had been used in the landfill gas recovery industry and modified the default parameters to provide conservatively high estimates of gas generation when the user inputs only tons of solid waste deposited in the landfill per year. The user has the option of conducting onsite tests to determine site-specific values for a gas generation rate constant and total potential methane yield (Ref. 22).

8.2 Other Models

Several consulting companies in the US have developed their own proprietary models that are used in design of gas collection and control systems. They include CH2M HILL, El-Fadel, Findikakis and Leckie (Ref. 23), and a few others. However, very little has been published in this area, as companies wish to protect the proprietary information.

CH2M HILL has developed a model of gas generation that takes into account more site-specific factors than the USEPA model. The model has been used as the basis of design for landfill gas collection systems for over a decade. Gas generation is modelled by an exponential decay equation that approaches zero asymptotically. The equation was derived from a statistical analysis of observations of gas generation from decomposing municipal solid waste in a laboratory-controlled anaerobic environment. The model requires the user to input the moisture content and information about the composition of the waste as well as the number of tons of waste per year.

An article in the journal Waste Management and Research (Ref. 23) describes a numerical model that solved biochemical production differential equations using the Runge-Kutta method. However, this model required inputs of parameters that are not typically well known for landfills (such as pH and the acidogenic biomass death-rate constant). It has not been field-tested.

A 1992 study by USEPA (Ref. 24) attempted to derive an empirical model of gas emissions from easily obtainable data. However, none of the simple models considered achieved a correlation coefficient greater than 0.65 when compared with measured gas extraction rates from a population of landfills. The study found that the best predictor of gas generation was the mass of refuse. It found that the average *methane* production was 4.52 m^3/min. per million metric tons of refuse (144.7 ft^3/min. per million tons). The study found that this relationship could be used to predict gas production with a correlation coefficient of 0.50. (The somewhat better 0.65 correlation coefficient required knowledge of the depth of the landfill.)

A recent review of the state of the art in landfill gas generation modelling by Huitric and Soni was published in the SWANA 20th Annual Landfill Gas Symposium Proceedings (March 1997). The review focused on variations of the first-order decay model and derived site-specific values for them

that are representative of Los Angeles area landfills. The review concluded that there are no significant differences between the first order model implementations (when appropriate rate constants and ultimate production parameters are used), and that zero-order models performed poorly by comparison.

Generally, experience indicates that the USEPA model of gas generation produces conservatively high estimates of gas generation, particularly in the post-closure period. Using mathematical models to estimate gas production is useful in designing systems to control gas at the source, but cannot be used to predict the rate or direction of gas migration from an uncontrolled source.

9. Long-term Health Effects

9.1 Summary of Risk Assessment Principles

The literature sources indicate that methane *per se* does not appear to have any health effects other than as an asphyxiant by displacement of air, and the potential for injuries resulting from explosion. No data were found on either short- or long-term methane toxicity or any current related toxicological studies.

However landfill gas, which contains other compounds as discussed earlier, has the potential for long term health effects resulting from the presence of these compounds. The risk assessment process offers a means to establish the potential human health or ecological effects of landfill gas, as well as risk associated with explosive properties of methane.

Risk assessment is a systematic process for evaluating the potential for adverse effects that may arise from a set of conditions, in this case the potential for exposure to landfill gas. Human health risk assessment is the evaluation of the probability of adverse health consequences to humans by exposure to a chemical at a given site. It takes into consideration that many chemicals may be present simultaneously in several media at once such as food, air, water, soil, dust, etc., and that the chemicals can reach human receptors through multiple exposure pathways.

In the case of landfill gas, the receptor may be the public in an off-site building which is subjected to chronic concentrations of landfill gas containing potentially toxic or carcinogenic materials such as the VOCs listed earlier, or the receptor may be a landfill worker who experiences exposure only during an 8 hour working shift occurring five days per week over the period of his employment. In both cases the pathway is the same: human exposure through the inhalation of gases.

Standard exposure models estimate the intake of a chemical through various pathways such as inhalation, ingestion, and dermal contact, and are used to estimate the total exposure of an individual, and the risk of human health impact (e.g. cancer or other risk).

9.2 Application of Risk Assessment Approach

There are four major elements that must be considered in a human health risk assessment, as follows:

Hazard Identification/Problem Formulation: This is the determination of whether a particular contaminant is present, and the identification of all key adverse effects (e.g. environmental persistence, toxicological effects and other health effects such as diseases and aesthetic effects)

Dose Response Measurement: Determination of the quantitative relationship between the magnitude of exposure and the probability of occurrence of a particular adverse effect as well as the uncertainties associated with the determination;

Exposure Assessment: Determination or estimation of the magnitude, frequency, duration and routes of exposure for the contaminant and assessment of the uncertainties associated with the determination;

Risk Characterization: Integration of the results of the exposure and dose response assessments to describe the nature and magnitude of the risk from each route of exposure, the receptors at greatest risk, and the uncertainties associated with the overall analysis

Both CCME and Ontario MOEE provide guidance documents on the application of the risk assessment process to both human health and ecological receptors.

9.3 Use of Specialists

Human health and environmental risk assessments can be complex processes requiring the knowledge of several environmental disciplines; it is recommended that, if there are concerns regarding the potential for human health or ecological impacts, a qualified specialist be retained to perform the risk assessment to ensure that it is correctly done and is acceptable to regulatory agencies.

10. Recommended Approach to Methane Management

Based on the information presented in this document, an approach was developed to methane management in areas situated close to active and closed municipal landfills. The approach outlined below includes action level criteria, a description of the actions to be taken, and the rationale for the selection of the specific levels and actions. The approach is similar to that taken by the City of Winnipeg, but has incorporated various concepts taken from other jurisdictions and organizations, to provide a comprehensive program of monitoring, and preventive and remedial activities.

10.1 Landfill Perimeter Monitoring and Action Level Criteria

Source control of any pollutant is typically the most cost-effective means of control. Consequently, monitoring and control of methane within the landfill or at the landfill boundary is considered the most reasonable first step in methane gas control around an active municipal landfill. It is recommended that this includes sub-surface and underground measurements of methane, and gas pressure (see Section 3.2). As a minimum, quarterly monitoring should be conducted for all landfills. If the methane monitoring demonstrates that gas migration is occurring, then sampling should be undertaken for non-methane organic compounds (NMOCs) to assess the potential for other impacts. This approach will provide a good indication of the potential for off-site migration of excessively high concentrations of methane, as well as for the presence of substances that may pose human health risks.

To minimize the potential for off-site migration of potentially hazardous concentrations of methane, an action level criterion of 50,000 ppm (100% LEL or 5% by volume) methane in soil gas is recommended. Limiting the landfill boundary concentration to the LEL will effectively prevent the accumulation of dangerous levels of methane in off-site structures. This approach is consistent with the risk assessment approach to contaminated site management, which requires that sites be managed in such a way to prevent ecological and human health impacts from hazardous materials on the site or migrating off-site.

For all landfills, it is expected that the landfill owner should be responsible for preventing methane migration, by installing passive or active methane control systems. However, if a proponent wishes to develop a property in the vicinity of an existing active or closed landfill, in spite of the potential for methane migration, then the developer should be responsible for assessing the extent of methane contamination, and incorporating mitigative measures into the development plan. This will require the developer to retain a qualified professional to conduct soil and building monitoring as described in this document.

10.2 Surficial Geology

As part of any methane gas monitoring program which requires the installation of boreholes for purposes of underground methane concentration and pressure measurements, soils should be logged

so that the nature of the surficial geology can be ascertained and potential methane migration pathways identified.

10.3 Subsurface Monitoring on Properties Adjacent to Landfills

Properties immediately adjacent to landfills should be subjected to regular monitoring for methane if inhabited structures exist on or are planned for the property. The gas monitoring probes placed at the perimeter of the landfill by the landfill owner may serve as adequate to detect migration onto the property, but it should be the property owner's responsibility, as well as the landfill owner's, to ascertain that this is so.

Monitoring probes on the property adjacent to the landfill, beyond the landfill perimeter, are generally necessary only if gas migration at the landfill boundary is detected, or if no perimeter monitoring program is in place at the landfill and gas migration beyond the property boundary may be occurring.

The locations, depths, and designs of the gas monitoring probes on the property, selection of monitoring equipment, monitoring parameters and frequency should be determined by a qualified professional. The locations should be selected in such a way to define the plume adequately to be able to determine whether or not it has reached the structures on the property. As a minimum, methane concentration and soil gas pressure should be measured to adequately characterize the gas migration plume.

The following factors should be taken into account in setting up the gas monitoring program:

- soil conditions
- hydrogeologic conditions
- locations of manmade conduits for gas migration including gravel and sand backfill in utility conduit trenches
- the locations of existing and planned structures

If methane migration across the property boundary is detected, then it is recommended that non-methane organic compounds (NMOCs) be tested, to determine if any compounds having potential health effects are migrating as well. This should include the BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) and chlorinated solvents/compounds (e.g. perchlorethylene, trichloroethylene, vinyl chloride), as included in the USEPA Method 624 Volatile Organic Compounds list.

If the subsurface monitoring program on the property shows that gas migration has reached inhabited structures, monitoring inside the buildings should commence if either of the following conditions occur:

- The soil methane adjacent to the building is 5,000 ppm (10% LEL or 0.5% gas by volume) or greater and the soil gas pressure is 0.25 kPa or greater
- The soil methane adjacent to the building is 50,000 ppm (100% LEL or 5% gas by volume) or greater and the soil gas pressure is less than 0.25 kPa.

Mitigation measures to prevent further migration of methane from the landfill and to prevent entry of any gas into buildings should begin immediately upon detection of gas migration onto the affected property.

10.4 Monitoring Programs for Off-Site Buildings

If subsurface gas probes detect methane migration onto the property that may have reached inhabited buildings, regular monitoring for methane in the buildings should commence. Concurrent efforts to define and then control the methane migration plume should be undertaken. Other volatile compounds in addition to methane should be tested if methane migration is known to be occurring.

A building monitoring program must take into account a number of factors, including the following:

- Sampling locations
- Sampling frequency
- Effects of temperature
- Effects of barometric pressure
- Surficial geology
- Potential concentrations
- Parameter selection

The following paragraphs provide guidance on each of the above factors.

10.4.1 Sampling Locations

Monitoring in a building should be conducted in a number of locations, including both ambient indoor air and confined spaces beneath and adjacent to the building where methane may accumulate. Sampling locations should include the following:

- Mid-air in all occupied and unoccupied areas of a building, and especially interior rooms where ventilation rates may be lower than other areas and methane could accumulate;
- Confined spaces such as wall cavities in both interior and exterior walls, crawl spaces, sumps/manholes;
- Potential Points of Entry (PoE) such as floor drains, sewer pipe entry points, floor/wall cracks, electrical or other conduits;

10.4.2 Sampling Frequency

Sampling frequency should be adjusted to take into account a number of factors including the following:

- Frequency of previous monitoring (if any);
- Concentration of methane (more frequent monitoring for higher concentrations);
- Exterior temperature (i.e. more frequent when ground frozen and gas migration potential is enhanced);

- Soil gas pressure (the higher the pressure the more frequent the monitoring);

For buildings which have been sampled previously, and no concentrations over 100 ppm have been found, quarterly sampling has been established by various jurisdictions as the minimum sampling frequency. A minimum of quarterly monitoring is recommended here.

In buildings which have not been sampled previously, an initial program of monthly sampling for 12 months is recommended to build up a database and establish trends in concentrations over the four seasons. As indicated in Table 10.1, if concentrations higher than 100 ppm are observed, monitoring should be adjusted to suit the actual concentrations.

10.4.3 Effects of Temperature

As discussed earlier, soil temperature will affect the potential for methane migration if the ground is frozen. Consequently, monitoring frequency should be increased in the winter months, typically November to April in Alberta. For example, if quarterly monitoring is required in a program, at least one of the samples should be collected while the ground is frozen. Similarly, in the Spring and Fall months when heavy rains or snow melt occurs, this may lead to the soil being saturated with water, and effectively impermeable to methane migration. At least one sample should be collected under these conditions as well.

10.4.4 Effects of Barometric Pressure

As indicated earlier, barometric pressure will have an effect on methane migration, and hence on sampling. Low atmospheric pressure will increase the net pressure differential driving methane migration, and could result in higher methane concentrations being measured in buildings. Consequently, some jurisdictions require that days of low barometric pressure be deliberately included in monitoring programs. If it is possible to incorporate days of low atmospheric pressure (i.e. an emergency situation does not exist), this should be accommodated. In any case, the barometric pressure must be recorded at the time of sampling.

Frequently, increased or reduced barometric pressure will result from the presence of HVAC and process exhaust systems. Monitoring should occur under normal operating conditions, as well as under shut-down conditions, to determine if methane accumulation could occur without the HVAC systems in operation. In all cases, both the exterior atmospheric pressure, and the interior barometric pressure must be recorded, as it is the pressure differential that is the driving force for methane migration.

10.4.5 Monitoring Parameters

When indoor air monitoring is performed, a number of parameters other than methane need to be tested and recorded, including the following:

- Moisture content of air (humidity)
- Temperature
- Barometric pressure (indoor and/or exterior; see above)
- Gas pressure (soil monitoring only)
- Meteorological history for previous week (i.e. potential for sealing of surface soils by rain or snow melt)

If LFG migration is kown to be occurring, it is recommended that non-methane organic compounds (NMOCs) also be tested, to determine if any compounds having potential health effects are present. This should include the BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) and chlorinated solvents/compounds (e.g. perchlorethylene, trichloroethylene, vinyl chloride), as included in the USEPA Method 624 Volatile Organic Compounds list.

10.5 Action Level Criteria for Off-Site Buildings

Recommended action level criteria have been developed to provide guidance on managing potential landfill gas hazards in buildings around landfills. These guidelines have been developed without reference to "sensitive uses", as all uses may be sensitive from a risk assessment perspective, if they involve being occupied by people. As indicated earlier, besides the risk of explosion from methane, landfill gas may contain chemicals that have potential human health impacts. The action level criteria described below have been developed based on explosion hazard, since the other human health aspects are very site specific.

An approach has been developed which provides criteria for indoor air/confined space, point of entry, and soils applicable to routine methane monitoring programs. The approach ensures a rational progression of actions to be taken under increasingly severe circumstances. Table 10.1 provides the action level criteria and a brief description of the rationale and actions to be taken. As indicated earlier in this report, there is no clearly developed scientific rationale for the selection of action level criteria in the literature reviewed. As far as was possible, concentrations have been selected applying rational scientific and engineering principles, although the safety factor approach had to be invoked in some circumstances.

10.5.1 Indoor Air/Confined Spaces

For existing developments on properties immediately adjacent to landfills, indoor air quality monitoring should be conducted on a regular basis if methane concentrations in soils at the landfill boundary are known to exceed the LEL. Both ambient air and confined spaces such as wall cavities and sumps should be tested. If the concentration in the indoor ambient air and confined spaces is <100 ppm, then the routine monitoring program of quarterly monitoring can be continued.

If the concentration of methane exceeds 100 ppm but is less than 500 ppm, then it should be determined if there is a methane source related to activities in the building such as natural gas, process chemicals, methanogenesis under anoxic conditions in sumps or under floor slabs, etc. If the methane source appears to be external to the building, an enhanced monitoring program should be initiated based on site-specific factors, as indicated in Table 10.1. In addition, the Points of Entry (PoEs) should be identified.

If the concentration of methane in ambient air/confined spaces is >500 ppm but <5,000 ppm, the concentration should be confirmed with a second instrument. A qualified professional should be consulted. An enhanced monitoring program should be implemented as required by site-specific conditions, including subsurface soil monitoring if it has not already begun at the landfill perimeter.

If the ambient air/confined space methane concentrations exceed 5,000 ppm (10% LEL, as in the US National Fire Code), the building must be evacuated immediately and appropriate ventilation should be implemented to reduce the concentration to <5,000 ppm. The test(s) should be verified with a second instrument. Ventilation should be continued, to keep the concentration below 5,000 ppm. Detailed soil investigations should be completed immediately as prescribed by a qualified

professional, and permanent mitigative procedures should be designed by a qualified professional and implemented as soon as possible. Once the mitigative measures have been implemented and the concentration has been reduced to <500 ppm, the building can be re-occupied.

10.5.2 Point of Entry

If the Point of Entry (PoE) concentration is >100 ppm but <500 ppm, then an enhanced monitoring program should be implemented consistent with site-specific conditions. If the PoE is > 500 ppm, then an enhanced monitoring program should be implemented, including preliminary soil gas monitoring external to the building but within 5m of the building wall.

10.5.3 Soil

A corrective measures program should be implemented consistent with the site-specific conditions, and may include building ventilation, sealing of points of entry, and soil venting, if either if the following conditions exists:

- The soil methane adjacent to the building is 5,000 ppm (10% LEL or 0.5% gas by volume) or greater and the soil gas pressure is 0.25 kPa or greater
- The soil methane adjacent to the building is 50,000 ppm (100% LEL or 5% gas by volume) or greater and the soil gas pressure is less than 0.25 kPa.

It should be noted that whenever elevated concentrations of methane are detected, that the integrity of any natural gas services in the building should be checked prior to any extensive monitoring or corrective measures specific to landfill gas migration are implemented.

TABLE 10-1
PROPOSED ACTION LEVEL CRITERIA FOR OFF-SITE BUILDINGS

Methane Level	Rationale	Actions
Indoor Air/Confined Spaces		
0 – 100 ppm	• 100 ppm distinguishable above background	• **Initial Monitoring** – monthly for 12 months, for buildings not previously monitored; if concentrations in mid-air, sumps/manholes, wall cavities, other confined spaces, potential points of entry (e.g. floor/wall cracks, drains, conduits), etc. exceed 100 ppm, implement enhanced monitoring suitable to concentrations listed in this table.
0 – 100 ppm	• 100 ppm distinguishable above background	• **Routine monitoring** – quarterly in mid-air, sumps/manholes, wall cavities, other confined spaces, potential points of entry (e.g. floor/wall cracks, drains, conduits).

100 – 500 ppm	• Potential indicator of methane migration	• Verify if methane source in the building (e.g., natural gas, process chemicals, etc.)
		• If methane source appears to be external to building, implement enhanced monitoring program based on site specific factors, including
		  • Measured concentration
		  • Climatic conditions
		  • Surficial geology
		  • Proximity to landfill
		  • Historical trends in methane gas concentration
		• Identify points of entry (PoE)

500 – 5000 ppm	• Below US National Fire Code evacuation level (10% LEL), but indicative of significant methane migration	• Confirm the readings with a second instrument • Consult qualified professional • Monitor as required by site specific conditions; include preliminary soil investigations, if not already underway at landfill perimeter • Implement corrective program based on site specific conditions (e.g. building ventilation, sealing of points of entry; soil venting, etc.)

Table 10-1
Proposed Action Level Criteria for Off-Site Buildings

Methane Level	Rationale	Actions

> 5,000 ppm	• Above US National Fire Code evacuation limit	• Evacuate building immediately
		• Confirm readings with a second instrument
		• Implement appropriate ventilation to reduce concentration to below 5,000 ppm
		• Conduct detailed soil investigations immediately
		• Design and install mitigative measures as recommended by qualified professional if:
		    • Soil methane concentration at building is ≥ 5,000 ppm (10% LEL or 0.5% by volume) and soil gas pressure is ≥ 0.25 kPa
		    • Soils methane concentration at building is ≥ 50,000 ppm (100% LEL or 5% by volume) and soil gas pressure is ≤ 0.25 kPa

Point of Entry		
100 – 500 ppm	• Potential indicator of methane migration	• Verify if building activities have caused readings • If no other explanation, implement enhanced monitoring program based on site specific factors, as described above
>500 ppm	• Potential indicator of elevated soil methane concentrations	• Implement enhanced monitoring program, including soil gas monitoring external to building
Soil (within 5m of building)		

5,000 ppm
(10% LEL)
	• Provides a safety factor of 10 with respect to LEL to avoid exceeding the LEL inside the building	• If soil methane is ≤ 5,000 ppm (10% LEL or 0.5% by volume) and soil gas pressure is ≤ 0.25 kPa - no need to design and install mitigative measures, but continue to monitor soil gas at same frequency as for Indoor Air/Confined Spaces
		• Design and install mitigative measures as directed by a qualified professional if:
		    • Soil methane concentration at building is ≥ 5,000 ppm (10% LEL or 0.5% by volume) and soil gas pressure is ≥ 0.25 kPa
		    • Soils methane concentration at building is ≥ 50,000 ppm (100% LEL or 5% by volume) and soil gas pressure is ≤ 0.25 kPa

11. References

1. "Standards and Guidelines for the Mitigation of Methane Gas at Buildings and Utilities", City of Winnipeg, Solid Waste Department May 1997.
2. "Guideline for Assessing Methane Hazards from Landfill Sites", Ontario Ministry of Environment, 1987
3. "Study of Houses Affected by Hazardous Lands", Canada Mortgage and Housing Corporation, 1992
4. Washington Administrative Code Section 173-351-200 (4)
5. "New Standards for Landfilling Sites, Proposed Regulatory Standards for New Landfilling Sites Accepting Non-Hazardous Waste", MOEE, Ontario, June 1996
6. Emcee Associates, Methane Generation and Recovery from Landfills, Ann Arbour Science, 1980, p. 86
7. Coleman, et. al., Identification of Landfill Methane Using Carbon and Hydrogen Isotope Analysis, 16th International Madison Waste Conference, University of Wisconsin-Madison, 1993.
8. USEPA Subtitle D Study, Phase 1 Report, 1986. EPA/530-SW-86-054.
9. A Compilation of Landfill Gas Field Practices and Procedures, Solid Waste Association of North America, Silver Spring, MD, 1992.
10. Metcalfe and Eddy, Inc., Wastewater Engineering, Collection and Pumping of Wastewater, McGraw Hill, 1981.
11. Burcik, E., Properties of Petroleum Reservoir Fluids, HRDC Press, 1979, p. 12
12. E.A. McBean, F.A. Rovers and G.J. Farquahar, Solid Waste Landfill Design and Engineering, Prentice Hall PTR.
13. Environment Canada "Canadian Climate Normals - Frost, 1951-1980", 1982
14. Alberta Municipal Act, Subdivision and Development Regulation 9AR 212/95, Province of Alberta, Aug. 25, 1995
15. "Landfill Criteria for Municipal Solid Waste", BC Environment, June 18, 1993
16. "Land Use On or Near Landfills and Dumps", Guideline D-4, Ontario Ministry of Environment, April 1994
17. "Policy Regarding Building Permits Adjacent to Landfills", City of Winnipeg, Water and Waste Department, Solid waste Division, May 1997
18. "Managing Landfill Gas at Municipal Solid Waste Landfills", SWANA, 1993
19. "A Compilation of LFG Field Practices and Procedures", SWANA, March 1992
20. "Waste Management paper No. 27 – The Control of Landfill Gas", 1989

21. "The Wild World of Landfill Gas Flares", Landfill Gas Specialties Inc., Ohio

22. Standard of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfills (NSPS), USEPA, Federal Register, March 12, 1996.

23. El-Fadel, Findikakis and Leckie , Waste Management and Research Vol. 7, pp. 31-42, 1989)

24. Peer, et. al., US EPA Document EPA-600/R-92-037, 1992.

Appendix A

List of Reviewed Literature

List of Reviewed Literature

1. "Guidance Document for Landfill Gas Management" Environment Canada, 1996.
2. "Guideline for Assessing Methane Hazards from Landfill Sites", Ontario Ministry of Environment, 1987.
3. "New Standards for Landfilling Sites, Proposed Regulator Standards for New Landfilling Sites Accepting Non-Hazardous Waste", MOEE, Ontario, June 1996.
4. "Guidance Manual for Landfill Sites Receiving Municipal Waste", MOEE, Ontario, Nov. 1993.
5. "Guide for Applying for Approval of Waste Disposal Sites", MOEE, 1994.
6. "Land Use On or Near Landfills and Dumps", Ontario, 1994.
7. "Landfill Criteria for Municipal Solid Waste", BC Environment, 1993.
8. "Standards and Guidelines for the Mitigation of Methane Gas at Buildings and Utilities", City of Winnipeg Water and Waste Department Solid Waste Division, May, 1997.
9. "Subdivision and Development Forms Regulation" (AR 212/95), Alberta, August 25, 1995.
10. Code of Practice for Landfills, Alberta Environmental Protection.
11. "Canadian Climate Normals - Temperature, 1957-1980", Volume 2, 1982.
12. "Canadian Climate Normals – Temperature and Precipitation, Prairie Provinces, 1957-1980", 1982.
13. "Kitchener Landfill Gas Utilization Project", Environment Canada, Aug. 1987.
14. "Kitchener Townhouse Study", CHMC, 1989.
15. "Study of Houses Affected by Hazardous Lands", CMHC, 1992.
16. "Soil Gases and Housing, A Guide for Municipalities", Canada Mortgage and Housing Corporation (CMHC), 1993.
17. "Field Tests of Remedial Measures for Houses Affected by Hazardous Lands", CHMC, 1995.
18. "Sanitary Landfill Study, Effect of Season and Landfill Leachate and Gas Production", University of Waterloo Research Institute, Volume II, 1972.
19. For Presentation at the Air & Waste Management Association's 90th Annual Meeting & Exhibition, Toronto June 8-13, 1997
    - Protection of buildings from methane; A UK designer's perspective
    - Control of Landfill Gas from Landfills and/or Marsh Areas (BC)
    - Control and Monitoring of Landfill Gas Underground Migration at the City of Montreal Sanitary Landfill Site

- From Mortgage Default to Re-occupation: The Odyssey of the Kitchener Townhouses
- Tackling the Problems of Closed Landfill sites, UK
- A Method to Evaluate Soil Gas VOC Influx into Houses
- Evaluating Remedial Measures for Soil Gas Infiltration: Lessons Learned from Field Studies, Kitchener

20. "Landfill Gas Energy Utilization: Technology Options and Case Studies", US EPA, June 1992.

21. "Air Emissions from Municipal Solid Waste Landfills - Background Information for Final Standards and Guidelines", US EPA, 1995.

22. "Enabling Document for The New Source Performance Standards and Emission Guideline for Municipal Solid Waste Landfills" US EPA, 1996.

23. "Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources", US EPA, 1996.

24. "A Guide for Methane Mitigation Projects", US EPA, January 1996.

25. "Design Procedures for Landfill Gas Interception, Collection, and Extraction Systems Pursuant to the Proposed EPA Regulations. For the Control of Landfill Gas" US EPA.

26. "Managing Landfill Gas at Municipal Solid Waste Landfills", SWANA, 1993.

27. "A Compilation of LFG Field Practices and Procedures", SWANA, March 1992.

28. "Waste Management Paper No. 27 - The Control of Landfill Gas", London England, 1989.

29. "Subsurface Landfill Gas Monitoring Strategies in California", California Integrated Waste Management Board (CIWMB), 1997.

30. "CIWMB Landfill Gas Monitoring Procedures". California Integrated Waste Management Board.

31. "Control of Gaseous Emissions from Active and Inactive Landfills (Rule 1150.1)", California, South Coast Air Quality Management District (SCAQMD).

32. "Guidelines for the Implementation of Rule 1150.1", SCAQMD

33. "Combined SCAQMD/CIWMB Regulations Division 2, Title 27", California.

34. "Methane Seepage District Regulations", Los Angeles, California.

35. "The Landfill Testing Program: Data Analysis and Evaluation Guidelines" California Air Resources Board, Stationary Source Division, 1990.

36. "Solid and Hazardous Waste Management Regulations", New Jersey.

37. "Recovery, Processing, and Utilization of Gas from Sanitary Landfills", prepared for the Municipal Environmental Research Lab, Cincinnati, OH. Feb. 1979.

38. Case Study of Landfill Gas Management at the Mission Hills Landfill MountainGate Country Club", GSF Energy Inc.

39. "Pre-Test Checklist for Successful Emission Testing of Enclosed Landfill Flares", Oklahoma.

40. "Concepts of Flare Design", Linklater Corporation, Kentucky, 1993.

41. "The Wide World of Landfill Gas Flares", Landfill Gas Specialties Inc., Ohio.

42. "Gas Collection Beneath a Geomembrane Final Cover System", CH2M Hill.

43. "Attenuation of Methane and Nonmethane Organic Compounds in Landfill Gas Affected Soils" Journal of the Air and Waste Management Association, December 1997.

44. "Identification of Landfill Methane Using Carbon and Hydrogen Isotope Analysis", Sixteenth International Madison Waste Conference, September 1993.

45. "Environmental Isotope Characteristics of Landfill Leachate and Gases". Groundwater. Vol.34, No.5, pp.827-836, 1996.

46. Heath Consultants Limited, Product Catalogue.

47. Inventus Technologies, Product Catalogue.

48. Solid Waste Landfill Engineering and Design, E.A. McBean, F.A. Rovers and G.J. Farquhar. Prentice Hall PTR.

49. Landfill Gas: From Environment to Energy. Commission of the European Communities, 1992.

50. Design, Construction and Monitoring of Landfills, Second Edition. John Wiley & Sons Inc., 1994.

Appendix B

List of Contacts

List of Contacts

Brock Rush, P.Eng.
Regional Engineer
Alberta Environmental Protection
Prairie and Eastern Slopes Regions
Calgary, AB
(403) 297-7884

Klas Ohman, P.Eng.
Operations and Development Engineer
The City of Calgary
Engineering and Environmental Services Department
Solid Waste Services Division
Calgary, AB
(403) 230-6613

Rick Valdarchi, P.Eng.
Special Project Engineer
The City of Calgary
Engineering and Environmental Services Department
Solid Waste Services Division
Calgary, AB
(403) 230-6614

Calgary Regional Health Authority
Population Health
Calgary, AB
(403) 228-7400

Alan Yee
City of Edmonton
Asset Management and Public Works
Waste Management Division
Edmonton, AB
(403) 496-5405

Roy Neehall
City of Edmonton
Asset Management and Public Works
Waste Management Division
Edmonton, AB
(403) 496-5405

Dr. Steve Hrudy
University of Alberta
Environmental Health Department
Edmonton, AB
(403) 492-3111

Nicole Kohnert, P.Eng.
Assistant Project Engineer
GVRD Solid Waste Department
Vancouver, B.C.
(604) 436-6823

Ken Wright
Development Services Department
Town of Coquitlam
Coquitlam, B.C.
(604) 664-1551

Rock Bertulucci
Building Department
Town of Richmond
Richmond, B.C.
(604) 276-4161

Russ Haycock
Environmental Services Department
Delta, B.C.
(604) 946-3282

Colin A. Potter, C.E.T.
City of Winnipeg
Water and Waste Department
Solid Waste Division
Winnipeg, MB
(204) 986-4463

Larry Wilcox
Ontario Ministry of Environment and Energy
Waste Reduction Branch
North York, ON
(416) 325-4440

Andy Campbell
Regional Municipality of Waterloo
Environmental Engineering Department
Waste Management Division
Waterloo, ON
(519) 575-4777

Phil Wilson
City of London
Environmental Services Department
London, ON
(519) 661-4587

Kevin Vibert
City of Toronto
Waste and Water Department
Toronto, ON
(416) 397-0203

Mike Sims
City of Oshawa
Enginnering Department
Oshawa, ON
(905) 725-7351

Richard P. Bielen, PE
Chief Systems and Application Engineer
US National Fire Protection Association
e-mail address: rbielen@nfpa.org

Dr. David Hickock
Director, King County Health Department
Seattle, WA
(206) 296-4807

Greg Bishop
King County Health Department
Seattle, WA
(206) 296-4785

Michelle Cardinal
Policy Development, MOEE
Toronto, Ontario
(416) 323-4463

Jim Mulira
Senior Engineer, MOEE
Toronto, Ontario
(416) 327-6986

Brian Grant
BC Environment
(250) 356-9834

Duncan Milne
Inventus Technology

Calgary, Alberta
(403) 250-5564

Scott Collins
Sales Representative, GasTech Canada
Calgary, Alberta
(403) 291-4700

Garry Eade, C.E.T.
Heath Consultants Limited
London, Ontario
(519) 659-1144

Appendix C

Terms of Reference

Alberta
ENVIRONMENTAL PROTECTION

Environmental Regulatory Service

203 Deerfoot Square
2938 11 Street NE
Calgary AB T2E 7L7

Telephone (403) 297-7884
Fax (403) 297-5944

January 21, 1998

MR. DAVID TAYLOR
CH2M GORE & STORRIE LIMITED
1500, 555 - 4 AVENUE S.W.
CALGARY AB T2P 3E7

Dear Mr. Taylor

RE: REQUEST FOR PROPOSAL FOR METHANE GAS STUDY

In order to accommodate existing and proposed developments adjacent to active and inactive landfills, Alberta Environmental Protection is funding the development of guidelines addressing the issue of methane gas and its impacts. Currently, no such guidelines exist within the province of Alberta. We are requesting proposals for the development of Alberta specific guidelines that address the terms of reference in the following section.

Terms of Reference

Conduct a literature review of existing Canadian and U.S. guideline/legislative requirements and develop a standard procedure guideline that is applicable to Alberta's geological and climatic conditions. The guideline should include, but not be limited to:

1. Action level criteria, including rationale for:
   - i. indoor air methane concentration levels of 0-50,000 ppm (acute and chronic exposure),
   - ii. point of entry concentration levels (e.g. floor cracks and utility conduits), and
   - iii. soil methane concentration levels adjacent to buildings;

2. Methane level determination procedures including sampling methods, sampling frequency and other relevant issues;

3. Indicators that assist in characterization of methane sources. This might include specific compounds which differentiate methane that is from a landfill, sewer, or natural source; soil characteristics and conditions; weather conditions; mechanical influences (e.g. building HVAC systems), etc.;

4. A discussion of the following issues:
    i. The significance of seasonal variability on methane production, migration and gas accumulation.
    ii. Land-use planning issues near known methane sources that are consistent with the Alberta Municipal Government Act, Subdivision and Development Regulation (AR 212/95).
    iii. Site mitigation, abatement and control measures that have proven successful.
    iv. The use, if applicable, of methane and landfill gas generation information in determining the future generation potential of a landfill.
    v. Long term health effects of exposure to methane or landfill gas.
    vi. Any other pertinent issues.

Project Schedule

The proposal shall indicate the ability to complete the project in accordance with the following schedule.

Issue Request for Proposal	January 21, 1998
Proposal Submission	January 30, 1998
Award Project	February 6, 1998
Interim Meeting	Feb/March, 1998
Draft Report	March 20, 1998
Meeting to Discuss and Finalize Report	March 27, 1998
Final Report	April 9,1998

Deliverables

The deliverables for this project shall include:

1. 3 bound copies of the Draft Report;
2. 3 bound copies of the Final Report;
3. 3 unbound copies of the Final Report; and,
4. 1 electronic copy of the Final Report,
   addressing the issues specified in the above terms of reference.

The proposal shall include a list of the project team members (including resumes), charge out rates and expected time allocations and disbursements. Alberta Environmental Protection is G.S.T. exempt.

The successful consultant will be expected to meet with Alberta Environmental Protection, at the Calgary, Alberta office, to discuss the draft and finalize the report. We anticipate that this meeting will be held one week following the submission of the draft report.

Project Contact

Mr. Brock Rush
Regional Engineer
Alberta Environmental Protection
Environmental Services
203, 2938 11 Street N.E.
Calgary, AB T2E 7L7
Ph: (403) 297-7884
Fax: (403) 297-5944
Email: brush@env.gov.ab.ca

Please submit 4 copies of your proposal to the attention of Brock Rush by mail or fax before 4:30 pm, January 30, 1998.

Sincerely

Brock Rush, M. Eng., P. Eng.
Regional Engineer